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NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO MEETING PROCEEDINGS 86

Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures

(Désorientation spatiale dans les véhicules militaires: causes, conséquences et remèdes)

Papers presented at the RTO Human Factors and Medicine Panel (HFM) Symposium held in La Coruña, Spain, 15-17 April 2002.

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RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

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- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS Studies, Analysis and Simulation Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

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Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures

(RTO MP-086 / HFM-085)

Executive Summary

Spatial disorientation (SD) is a condition characterised by the failure of the operator to sense correctly the position attitude or motion of the vehicle, or of him/herself, within a fixed co-ordinate system provided by the surface of the earth and the gravitational vertical. SD has afflicted pilots since the early days of powered flight, yet despite an understanding of the causes of SD, improvements in the display of information on spatial orientation and greater emphasis on SD training, accidents primarily attributable to SD continue to occur. In contrast to the overall accident rate, which has fallen progressively over the past 30 years, the SD accident rate has remained more or less constant for the last 15 years. This would appear to be due, at least in part, to the introduction of new technologies, such as Night Vision Goggles, that have allowed operations in environments which previously were not possible. In view of the apparent lack of progress in combating SD and the continuing loss of life and aircraft, the Human Factors and Medicine Panel (HFM) considered it to be timely for the topic of SD to be revisited in the light of emerging techniques and technologies which might have application not only to SD in flight but also to other military environments. The resulting Symposium, entitled 'Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures', was held in La Coruña, Spain, on 15-17 April, 2002, at which 1 keynote, 32 oral and 14 poster presentations were made.

Despite the wide-ranging scope of the call for papers relating to SD in land, sea and air operations, the greater proportion of the papers dealt with SD in flight. Results of questionnaire surveys in four countries confirmed the ubiquity of SD incidents in military aviation and showed the importance of visual illusions, distraction and lack of crew co-ordination, in addition to the well recognised vestibular illusions, as causal factors. This information is of value both in training and in the understanding of accidents in which SD may be implicated. Eight papers reviewed the SD training of aircrew. The use of some form of ground-based rotatory device to demonstrate various illusions is common practice, but there would appear to be benefit in the use of a full-mission, motion-based simulator to demonstrate realistically SD scenarios.

SD during and following combat manoeuvres in an agile aircraft is postulated but, as yet, not documented. Centrifuge simulations in which aviators were exposed to changes in bodily orientation during $+G_z$ load, or to transient $+G_z/G_y$ or $+G_z/G_x$ stimuli, revealed large individual differences in the sensations and in the intensity of disorientation evoked. Further work is required to identify population norms and for comparison to be made with observations in flight, where an increased $+G_z$ acceleration is associated with lower angular rates and lower Coriolis accelerations than in a centrifuge.

The most important advance of recent years with the potential to combat SD has been the use of tactile stimuli to give information on spatial orientation. The value of the Tactile Situation Awareness System (TSAS) (developed by the US Navy) has been shown to reduce errors in maintaining hover, in both actual and simulated helicopter flight, when TSAS was active and that the system reduced subjective workload. It was also shown to be effective in cueing TF climb/dive commands, tactical lateral steering and flight director guidance, and location of threats. Other simulator experiments have demonstrated the benefit of a tactile display in countering the decrement in performance in the hover that occurred when the pilot's workload was increased by a secondary task. These experiments substantiated the claim that tactile cues are 'intuitive' and are processed at a low level within the central nervous system and do not make claim on higher level resources. TSAS coupled to a GPS receiver has been shown to aid Special Tactics forces by indicating cross-track and glide slope errors during parachute descent, and, when on the ground, deviation from a pre-determined course and proximity to a designated

way-point. Tactile navigation cues have also been successfully employed by divers and pilots of high speed insertion craft to indicate deviation from track or of a craft's heading from that required to reach a target way-point.

Prevention of SD by the use of a system to monitor a pilot's functional state in order to detect any performance decrement was described. The proposed system would provide 'cognitive assistance' to the pilot and, if necessary, take over partial or full control of the aircraft if the pilot was incapacitated or flight safety compromised. The system is inchoate insofar as it has yet to be implemented in hardware. A number of laboratory experiments on visual displays and on perception of orientation of the visual vertical were presented. These were without immediate practical application but they have some relevance to the design of new head-mounted and cockpit displays.

The two descriptions of disorientation in land vehicles dealt with rarely encountered conditions, one a phobic postural vertigo of motor car drivers, the other an effect of the vibration and cyclical accelerations experienced by racing drivers. Difficulties of orientation and escape from the inverted hull of a rigid inflatable craft (RIC) identified the need for escape training comparable to that performed by helicopter crews.

Désorientation spatiale dans les véhicules militaires: causes, conséquences et remèdes

(RTO MP-086 / HFM-085)

Synthèse

La désorientation spatiale (DS) se caractérise, pour l'opérateur, par une incapacité à appréhender sa position, son attitude et sa trajectoire ou celles d'un véhicule, à l'intérieur d'un système de coordonnées fixes, déterminé par la surface de la terre et la verticale gravitationnelle. Depuis les premiers vols propulsés, les pilotes ont été affectés par la DS. Ses causes sont connues, des progrès ont été faits dans la distribution des informations et une plus grande importance a été accordée à l'entraînement DS et pourtant elle demeure encore la cause de nombreux accidents. Alors que le taux global d'accidents a progressivement diminué depuis 30 ans, celui lié à la DS est resté plus ou moins constant au cours des 15 dernières années. Une des raisons de ce niveau élevé pourrait être l'introduction de nouvelles technologies, telles que les lunettes de vision nocturne, qui permettent d'effectuer des missions dans des environnements inaccessibles auparavant. En raison de cette stagnation apparente dans la lutte contre la DS qui continue à entraîner des pertes d'avions et de vies humaines, la commission sur les facteurs humains et la médecine (HFM) a jugé opportun de réexaminer le sujet de la DS, à la lumière des nouvelles techniques et technologies qui pourraient être appliquées non seulement à la DS en vol, mais aussi à d'autres environnements militaires. Il a donc été décidé d'organiser à La Corogne, en Espagne, du 15 au 17 avril 2002 un Symposium intitulé « La désorientation spatiale dans les véhicules militaires : Causes, conséquences et remèdes » avec 32 présentations orales et 14 séances d'affiches.

Malgré le large domaine offert lors de l'appel aux textes de conférence, (opérations terrestres, maritimes et aériennes), l'essentiel des communications a porté sur la DS en vol. Les résultats de questionnaires distribués dans quatre pays ont confirmé la permanence des incidents DS dans l'aviation militaire et ont démontré que les causes principales étaient les illusions visuelles, le manque d'attention et d'éventuelle coordination entre membres d'équipage, en plus des illusions vestibulaires bien connues. Ces informations sont importantes tant pour l'entraînement que pour la compréhension d'accidents impliquant la DS. Huit communications portaient sur l'entraînement DS des équipages. L'utilisation au sol de dispositifs en rotation pour démontrer les différentes types d'illusions est maintenant généralisée, mais la mise en œuvre, pour une démonstration réaliste de scénarios DS, d'un simulateur avec système de mouvement pour la simulation intégrale des missions semble intéressante.

Pour les avions de combat très manœuvrants, l'impact de la DS pendant et après les phases de combat est parfaitement admise mais encore mal documentée. Des simulations en centrifugeuse avec des pilotes soumis à des changements d'orientation corporelle à $+G_z$, et à des stimuli transitoires à $+G_z/G_y$ ou à $+G_z/G_x$, ont révélé de grandes différences entre les individus en matière de sensation et d'intensité de désorientation. Des travaux supplémentaires sont maintenant nécessaires pour identifier les normes de chaque type d'individus. Il sera possible de les comparer avec les observations effectuées en vol, où l'augmentation des accélérations +Gz est associée à des vitesses angulaires moins élevées, ainsi qu'à des accélérations Coriolis moins fortes qu'en centrifugeuse.

L'avancée la plus importante enregistrée au cours des dernières années dans la lutte contre la DS a été l'emploi de stimuli tactiles pour donner des informations sur la désorientation spatiale. L'intérêt du Système Tactile de Conscience de la Situation (TSAS) (développé par l'US NAVY) a été démontré. Lorsque ce système est actif, on observe une réduction d'erreurs de maintien de vol stationnaire, tant en vol réel que simulé. En plus, le système a permis de réduire la charge de travail subjectif. Son efficacité a également été démontrée pour la signalisation des commandes piqué/cabré, le pilotage latéral tactique, le guidage du système central de vol, et la localisation de la menace. D'autres expériences en simulateur ont démontré les avantages du visuel tactile, qui permet de compenser, en vol stationnaire, la baisse de performances entraînée par l'augmentation, par des tâches secondaires, de la charge de travail du pilote. Ces expériences ont confirmé que la signalisation tactile est « intuitive », qu'elle est traitée à un niveau inférieur du système nerveux et qu'elle ne sollicite pas des ressources de niveau supérieur. L'intérêt pour les Forces Tactiques Spéciales d'un TSAS associé à un récepteur GPS a aussi été souligné. Il permet d'indiquer d'éventuelles erreurs de position transversale et d'alignement de descente lors du parachutage, et une fois au sol des écarts par rapport à la route prévue à proximité d'un point de cheminement désigné. Les systèmes tactiles de navigation ont également été utilisés avec succès par des plongeurs et des pilotes de vedettes rapides pour indiquer des écarts d'itinéraire ou de cap pour se rendre à un point donné.

La prévention de la DS grâce à un système permettant de contrôler l'aptitude opérationnelle du pilote afin de détecter toute dégradation des performances a été décrite. Le système proposé pourrait fournir de « l'assistance cognitive » au pilote et, le cas échéant, prendre le contrôle partiel ou total de l'avion au cas où le pilote serait frappé d'incapacité soudaine ou lorsque la sécurité du vol serait compromise. Le système est incomplet dans la mesure où la réalisation matérielle reste à faire. Un certain nombre d'expériences de laboratoire sur des dispositifs de visualisation, ainsi que sur l'orientation de la verticale visuelle ont été présentées. Si celles-ci n'ont pas d'application pratique immédiate, elles paraissent adaptées pour la conception des nouveaux visuels de casque et les écrans du poste de pilotage.

Les deux descriptions de la désorientation dans les véhicules terrestres ont porté sur des conditions rarement rencontrées, à savoir le vertige postural phobique chez les conducteurs de voiture, et les effets des vibrations et des accélérations cycliques subies par les pilotes de course. Les difficultés rencontrées en cas de retournement de radeaux de sauvetage rigides (RIC) pour s'orienter sous les coques rigides et pouvoir évacuer, ont mis en exergue un besoin d'entraînement à l'évacuation comparable à l'entraînement des équipages d'hélicoptère.

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Technical Evaluation Report

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Introduction

Spatial disorientation is characterised by the failure of the operator to sense correctly the position, motion or attitude of the vehicle, or of him/herself, within a fixed co-ordinate system provided by the surface of the earth and the gravitational vertical. Spatial disorientation (SD) in flight, where the operator is the pilot and the vehicle is an aircraft, has been a problem since the early days of powered flight, and is a topic that has been discussed on numerous occasions within the NATO community. Yet, despite an increased understanding of the multifactorial aetiology of SD and improvements in the display of information to the aviator to facilitate the perception of veridical spatial orientation (SO), accidents primarily attributable to SD continue to occur. Indeed, as technologies of manufacturing, quality control and aircraft maintenance improve, the proportion of accidents (*syn.* mishaps) due to SD has increased. This would appear to be due, at least in part, to the introduction of new technologies, such as night vision goggles (NVGs), that have allowed flight operations in environmental conditions which previously were not possible.

In view of the apparent lack of progress in combating SD and the continuing accident rate with its loss of life, loss of aircraft and high financial cost, the Human Factors and Medicine Panel of the Research and Technology Agency considered it to be timely for the topic of SD to be revisited in the light of emerging and recently developed techniques and technologies which might have application not only to SD in flight but also in other military environments.

The ‘Call for Papers’ issued in June 2001 solicited unclassified contributions on the following topics: 1) Lessons learned from over 40 years of SD studies in the aeronautical environment (Mechanisms involved, Predisposition to SD, Role of cognitive factors). 2) How non-mishap SD may negatively impact crew performance and mission effectiveness (Air environments, Land environments, Sea environments). 3) Potential predisposition to SD using various head-out devices, NVG, HUD, HMD etc. (Day/night missions, Over water, Influence of visual conditions). 4) Effects of artificial visual environments (Virtual environment immersion, Enhanced and/or synthetic vision systems in vehicle manoeuvring and weapon delivery). 5) Spatial disorientation in new vehicular environments (Results of testing supermanoeuverable aircraft, uninhabited vehicles etc., Display and control issues). 6) Underwater disorientation (Helicopter ditching at sea, SEALS operations, Submarines). 7) Traditional and innovative SD countermeasures for tri-servcice warfighters (Training devices and protocols, Onboard equipment, Cognitive and sensorimotor aids, Visual and auditory symbology, Peripheral visual information, Tactile displays). 8) Standardisation of SD issues (Data Collection, Training methodologies, Equipment characteristics)

Forty-eight of the abstracts submitted were chosen for inclusion in the programme of the Symposium that was held in an appropriately sized and well equipped theatre of El Palacio de Congresos, La Coruña, Spain, on April 15-17, 2002. Thirty-four abstracts were selected for oral presentation and 14 for presentation as posters. The oral communications were grouped into six sessions; 1) Recent advances in causal mechanisms. 2) Operational and psychological consequences. 3) SD in land sea and virtual environments. 4) SD training programs. 5) SD countermeasures and training tools. 6) Cognitive and sensory aids to (preventing *Ed.*) SD. The Symposium ended with a free ranging ‘Round Table’ discussion with contributions from the platform and the audience. At the Symposium, two oral communications and one poster were withdrawn.

TECHNICAL EVALUATION

Incidence of Spatial Disorientation

In the Air.

The ubiquitous nature of SD in flight was revealed by three questionnaire surveys. Those carried out in the USAF (**7**) and the UK (**8**) employed similar questionnaires. Analysis of the responses of 2582 USAF and 752 (RAF, RN & Army) aviators were analysed and revealed generally comparable SD experiences, major differences being attributable to the small proportion of helicopter pilots in the USAF sample. Not surprisingly, 'the leans' was the most frequently reported type of SD (84%) followed by various visual illusions (76% - 40%). The causal factors: 'Distraction / Task saturation' (64%) and 'Poor crew co-ordination' (46%) featured highly in the ranking of responses; a finding that has important implications for SD training. 8% of the USAF aviators and 15% of the UK aircrew had experienced SD incidents of sufficient severity to adversely affect flight safety. In a SD questionnaire survey of 407 Hellenic Air Force pilots, 34% reported that they had never experienced an illusion in flight (**9**). Of those who had experienced SD, 'the leans' was the most frequently reported (47%). As in the USAF/UK surveys, 'Erroneous bank correction when using attitude indicator' or 'Flight instrument reversal' was not uncommon with incidences of 23%, 31% & 24% in the USAF, UK and HAF surveys respectively. A survey of 134 USArmy/National Guard aviators (**24**) found that 71% had experienced a SD incident in flight. The number reporting an SD experience was positively correlated with flight hours and ranged from 40% in those with less than 500 hrs to 100% of the pilots with 3500 – 4000 hrs in the air. In a study of 80 Spanish Air Force aviators (**12**), it was found that 73% of the fighter pilots had experienced SD but only 26% of transport pilots.

Incidence of SD accidents. Whereas SD experiences are generally common, accidents (*syn.* Class A mishaps) in which SD is implicated are relatively rare. No paper surveying accident statistics was presented at the Symposium but several authors quoted accident rates. For example, in the period 1992 – 2000, SD was a major or contributory factor in 20.2% of USAF Class A mishaps. US Army and US Navy rates over a similar period were 27% and 26% respectively (**7**). In the UK the proportion of SD related accidents over the past 30 yr. has ranged from 6% (Navy, 1972-1984), 12% (RAF, 1973-1991) and 21%(Army, 1971-1982) (8). In the Polish Air Force, some 8% of accidents were considered to be due to SD (**21**). USAF Class A mishaps rates over the period 1972-2000 show a progressive fall in the overall rate from 2.5 accidents per 100,000 flying hours in 1972 to a rate of 1.0 in the year 2000. In contrast, the SD accident rate has fallen from 0.5 to 0.25 over the same period and has been more or less constant for the last 15 yr. (**18**)

In Land Environments.

Three papers described SD in drivers of motor vehicles. Motorists Disorientation Syndrome (MDS) (**13**) is a condition in which the driver experiences an illusory veering or tilting of the car which can be so compelling as to cause inappropriate control. The condition is considered to be a functional disorder – nosologically a phobic postural vertigo – as it is not associated with any vestibular abnormality. The condition is not common and is amenable to treatment by cognitive behavioural therapy and desensitisation to motion stimuli.

The disorientation, dizziness, blurred vision and postural imbalance reported by race car drivers (**14**) is an even more esoteric condition than MDS as there are few who have driven on the modified Texas Motor Speedway. From an analysis of the trajectory of the car on the race track, the authors concluded that these symptoms were attributable to the cyclical acceleration, having peak intensities of 4.3 G_y and 3.0 G_z, which the drivers experienced twice each circuit of the track.

Drivers of an armoured vehicle experienced mild SD when using a binocular visual display that was driven by a head-slaved camera system mounted on the top of the vehicle (**46**), although more troublesome was the motion sickness induced when using the visual display. However, motion sickness scores were halved when the camera was (or cameras were) slaved to head position in pitch, yaw and roll than when there was no roll compensation. No significant differences were found between mono or stereo systems or with enhanced stereo. Paper 16 described an experiment involving the control of a small robotic vehicle carrying cameras to give a mono, stereo or enhanced stereo views to the remote operator. A task dependent benefit of the enhanced stereo was demonstrated.

Reference was made in paper **6** to a form of SD, characterised by errors in the spatial localisation of a visual target, as can occur whilst tracking on an anti-aircraft gun platform. In centrifuge experiments, in which a seated subject had to set a visual target to the perceived horizontal when exposed to an X axis acceleration, it was found that the depression of the horizon did not accord with the angular deviation of the resultant force vector. A significant depression of the horizontal occurred at a radial acceleration of only 0.014 m/s^2, where the deviation of the resultant force vector was only 0.08deg., but with a G_x of 1.5m/s^2, giving a resultant at 12deg, the horizon was depressed but 0.6deg. The reason for this apparent amplification of the oculogravic illusion at low radial accelerations and substantial suppression at higher intensities is covert.

In Water.

The SD and other difficulties experienced by those aboard on attempting to escape from a ditched helicopter are well recognised. However, paper **15** showed that the occupants trapped within a capsized rigid inflatable craft (RIC) can be in a worse predicament as they have to locate an escape hatch in the inverted hull. Several incidents in which the crew of capsized RICs failed to escape were described. These emphasised the need for better orientational cues to help those trapped within the dark of the inverted hull to find the escape hatch. A case was made for the crews of RICs to have escape training in a 'dunking' simulator, such as is currently practised by those who fly in helicopters.

Non vehicular.

Exercise induced intolerance is a recently described balance disorder in which symptoms of nausea, dysequilibrium and dizziness are precipitated by bouts of exercise involving head movement. Paper **41** presented the findings from a study of 15 military patients. All responded favourably to a tailored exercise programme with active and passive motion of head and body. After therapy, lasting on average 4.6 wk, they all returned to active duty, albeit with a recurrence of symptoms in four of the patients, three of whom were from the group of five smokers and one from the ten non-smokers.

Prophylaxis

General.

The three principal approaches to preventing SD, or at least reducing the frequency of SD incidents and accidents, were outlined in the Keynote Address, they are: 1) Selection and training, 2) improved displays for maintaining spatial orientation and for recovery from unusual attitudes (UAs), 3) Systems for the provision of pilot assistance, and autonomous systems for recovery from UAs and prevention of controlled flight into ground (CFIG). However, the speaker was not sanguine that SD accidents would ever be completely prevented either in military aviation or in the less well-regulated world of general aviation. Nevertheless, it is the objective of the USAF Research Laboratory's SD Countermeasure Program to reduce the SD mishap rate by some 50% in the next 5 yr. and eventually eliminate SD as a significant factor in USAF mishaps (**18**).

Selection and Training.

No paper dealt with the topic of selection, but seven papers described the approach to SD training. These covered training in the USAF (**18**), US Army Air Force (**24**), and the Air Forces of France (**22**), Germany(**19**), The Netherlands (**20**), Poland (**21**), and the UK Army (**25**). All of the programmes had a common objective, namely: to help the aviator recognise SD, the flight conditions in which it was likely to occur, and to understand causal mechanisms. In all the countries, this objective was achieved by classroom lectures followed by some form of practical demonstration. Except in the UK Army, this SD demonstration is carried out on ground-based, motion devices which vary in complexity from a simple (Barany) rotating chair to a full-mission, dynamic simulator (**20, 21, 24**). Devices that are, in effect, short arm centrifuges, such as the ETC Gyrolab 2000 of the GAF (**19**) or an 'eccentric mode 3D rotating chair' (20), are used to demonstrate, *inter alia*, somatogravic and oculogravic illusions. The Générateur d'Illusions Sensorielles (Sensory illusion generator) employed in France (**22**) has a 3m arm with a cab having motion in pitch yaw and roll that can be controlled by the occupant. In Poland, a 9m arm centrifuge with a tilting gondola is deployed for SD training (**21**). The demonstration of visual illusions is no less important, perhaps even more important, than the demonstration of vestibular illusions, as visual problems are reported with high frequency in questionnaire surveys. Experience of visual illusions is provided by the use of the visual display of a SD trainer (**19**), a flight simulator (**20, 21, 22**) or a facility specifically designed for this purpose (**20,22**).

In some Air Forces a full-mission, flight simulator is used to give aircrew experience of scenarios in which SD can occur, or in which accidents have occurred, as well as to practise recovery techniques (**19**, **21, 24**). USAARL has developed "SD awareness scenarios", based on actual accidents, for SD training in helicopter flight simulators (**24**). Despite favourable comment by those who have flown the demonstration sorties, they have not been incorporated in most of the USArmy/National Guard simulator training programs because their use was not obligatory.

Validation of the effectiveness of SD training is fraught with problems. It is reassuring to have favourable reports from those being trained, but more meaningful is reduction in the SD accident rate. Unfortunately, accident rates are a noisy statistic, especially when the criteria for deciding if SD is a relevant factor are not clear-cut and are amenable to individual interpretation (**25**). Internal validations, made by those receiving instruction, do provide feedback to course organisers, although they are far from being an absolute measure. Thus the in-flight SD demonstrations carried out in the UK Army Air Force were rated as "extremely effective"(**25**), while the flight simulator scenarios of the US Army Air Force were considered to be "a great training experience". "Excellent" to "good" ratings were given to the demonstration of the 'graveyard spin', both with and without hands-on recovery, in the GAF Gyrolab 2000 trainer (**19**); demonstration of 'a dark take-off', 'the leans' and 'sub-threshold rotation' were less favourably rated.

It is to be regretted that the important question: What motion cues are really required for effective SD training? was not addressed by any of the Symposium participants. However, paper **23** described the kinematic modelling of a motion platform, having a mechanism with differing configurations of revolute and prismatic joints. The model could be employed to optimise transient or continuous motion cues which would engender perceptions of spatial orientation, or disorientation, comparable to those evoked by specific aircraft manoeuvres in flight, while not producing, or at least minimising, any deleterious side effects. The model incorporates vestibular system dynamics, but no consideration is apparently given to visual-vestibular interactions or to the role of the idiotropic vector in the perception of spatial orientation that feature in the model described in paper **1**.

Changes in postural and cognitive function following exposure to the motion stimuli of a ground-based SD demonstrator. Postural activity was increased in comparison with pre-exposure control levels and was greater in older pilots (39-50 yr. old) than in a younger group (20-25 yr. old) (**35**). Another study (**12**) of postural activity was carried out on 80 pilots after SD training on a 'Gyro GPT II' rotator. 'Computerized Dynamic Posturography' (Neurocom Equitest) revealed that the 'Vestibular Response' was depressed, relative to normative values following the demonstration. This effect was greater in a group of fighter pilots than in a group of transport pilots, and was considered to be indicative of a greater dependence on visual information by the fighter pilots. In another study (**11**), degradation of cognitive function, as indicated by performance of 'Letter Cancellation' and 'Digit Symbol Substitution' tests, was found following SD training in 'Gyrolab'. The investigation had adequate pre- and post-exposure controls and both tests showed significant impairment. It is an open question whether the decrement in performance is a specific effect of the motion stimuli, or is just an expression of reduced motivation to perform the tasks after more interesting and involving experience in the SD demonstrator.

Presentation of Information on Spatial Orientation

Visual.

Only two papers specifically addressed the topic of the visual display of information for aircraft orientation. The contribution of a chequerboard pattern to the peripheral, visual field was assessed by the magnitude of postural sway that movement of the pattern could induce in the viewer (**28**). The finding that there was still an effective stimulus when the peripheral field was limited to 105deg or when a central area of 20deg x 20deg was omitted, is compatible with earlier work on the postural effects of dynamic ambient visual cues. The other paper described an experiment that compared a 'moving horizon'(MH), a 'moving plane'(MP) and an 'arc segmented'(ASR) attitude display in a PC based flight simulator program (**30**). For both perturbed flight and UA recovery, the best performance was achieved with the ASAR display, despite the preference by the flight cadet subjects for the MH (inside-out) display. While the link between psychophysical responses and display symbology is of importance, it should be remembered that there is along way to go from laboratory experiments to operational implementation.

Other papers dealt with aspects of behaviour and perception with different visual displays. Contrary to expectation, pilots who wore a helmet mounted display (HMD) having a conformal horizon, attitude display, did not exhibit a head tilting response, i.e.the optokinetic cervical reflex (OKCR) when flying in simulated VMC (**44**). It was found that in both the simulated IMC and VMC phases of the flight requiring bank angles of up to 80deg, there was negligible head tilt. The lack of an OKCR was attributed to the pilots using bank and pitch scale information in the display to maintain their orientation in both experimental conditions.

Paper **29** describes a series of experiments which demonstrated the influence of a head mounted display on the perception of the vertical. Subjects were required to set a luminous, linear target to the perceived earth vertical when either the head or the frame of reference, in which the target line was displayed, were tilted in roll through angles of up to ±40deg. The largest errors (≈ 6deg) occurred when the HMD displayed a virtual frame (30deg x 23deg) that moved with the subject's head. Smaller errors were made when the frame in which the target line was displayed was tilted; they were least when the target line was presented within a circular frame. In a further set of experiments in which the subject was tilted bodily through angles of ±30deg from the vertical, the greatest errors (of up to 10deg) were again made when the HMD displayed a virtual frame that moved with the head. Errors were less when the HMD virtual frame moved with the tilting chair, and were least when the frame was circular.

The perceived visual horizontal was also shown to be influenced by the optical structure and textural features of the display in a centrifuge experiment in which subjects, facing radially, were exposed to X axis accelerations of 1.0, 1.5 and 2.0 G_x (**37**). In the dark, the visual horizontal, as indicated by the location of a single, moveable LED, was depressed by some 12deg at $2G_x$. When the LED was viewed against an illuminated background frame that could be tilted in pitch through ±20deg, the oculogravic illusion was substantially suppressed, and the location of the perceived horizon was then principally determined by the pitch angle of the background frame.

Human centrifuge studies of the influence of lateral ($+G_y$) and longitudinal/lateral ($+G_z/+G_y$) acceleration were carried out in order to investigate possible SD problems during manoeuvring in an agile aircraft (**2**). Perceived earth vertical was indicated by positioning a cruciform target in a head-up display, and apparent geocentric body attitude by indication on a semicircular scale. At lateral accelerations of 0.5 to 3.5 G_y the visual vertical was deviated in roll, albeit through a smaller angle than the resultant vector made to earth vertical except at 3.0 and 3.5 G_y. With combinations of longitudinal and lateral accelerations, the perceived roll angle was substantially less than the deviation of the resultant vector. In a further series of experiments to study the interaction of visual with vestibular/proprioceptive systems, it was found that in four subjects the illusory perception of roll decreased when the eyes were closed, whereas another two subjects exhibited the opposite effect. This increase in the somatogravic roll illusion was accompanied by reports of SD, such as: "a sense of endless roll", "constant roll to the right, "impossibility to determine spatial attitude". These dynamic perceptions of movement, in some cases a true vertigo, would appear to have occurred in a steady state force environment without concomitant angular stimuli.

Another centrifuge study, related to the simulation of the force environment of an agile aircraft, assessed the subjective effects of high angular accelerations in pitch or roll whilst under $+G_z$ load (**36**). Experienced centrifuge subjects were little disturbed by angular movements, having peak accelerations of 1-10rad/sec^2 in pitch or roll, through angles (of 5–27deg) calculated to give G_x or G_y components of 0.5-1.5G with G_z of 1-8 G. Subjective discomfort, on a scale of 0-10, rarely rose above a score of 4 ("movement felt but not disruptive") in any of the 26 experimental conditions in both pitch and roll. The subjective rating increased with the magnitude of the X or Y axis acceleration, but there was no effect attributable to the rate of the movement. Unfortunately the authors gave no information on the kind of sensations induced by the procedures nor did they discuss the relative contribution of the cross-coupled stimulus to the semicircular canals and the stimulus to the otolith organs that occurs with the change in the orientation of the head to the linear acceleration and angular velocity vectors.

Tactile

The use of tactile stimuli to give information for spatial orientation or other components of situational awareness is a maturing technology. Paper **31** described the Operational Utility Evaluation recently conducted on the Tactile Situational Awareness System (TSAS) developed by the US Navy over the past 10yr. Evaluations carried out in CV22 helicopter simulator and in flight in a MH-53M have shown that errors in maintaining hover, in both actual and simulated flight, were less when TSAS was active, and that the system reduced subjective workload. TSAS was also shown to be effective in cueing TF climb/dive commands, tactical lateral steering guidance, flight director guidance for instrument approaches, and location of threats – the latter being received most enthusiastically by the aircrew.

Evidence that the interpretation and utilisation of tactile cues did not impose a burden on the performance of a closed loop task was provided by measures of performance of a hovering task both with or without NVGs in a helicopter simulator (**49**). In both conditions, the presence of a tactile torso display improved performance, there being little difference between a simple tactile display and a more complex one. More significantly, the presence of the tactile display largely overcame the decrement in performance wrought by an aural secondary task, without increase in ratings of mental effort made by the pilots. These experimental results give substance to the claim that a tactile display can provide 'intuitive' cues for spatial orientation, or in other words, cues that do not require high level processing within the central nervous system. The study also found little difference in the performance enhancement produced by simple and complex torso display. Indeed, the latter could be disadvantageous as it is less 'intuitive' and has claim on higher level processing resources.

TSAS has been shown to be of assistance to Special Tactics Forces for navigation in the air and on the ground (**32**). A simple configuration of tactors on a belt, coupled to a Global Positioning System (GPS) receiver, was used by personnel engaged in 'High Altitude High Opening' operations to indicate cross-track and glide slope error during descent. For ground navigation, only three tactors were used to indicate deviation from a predetermined course or proximity to a designated waypoint. Operator performance was better and deviations from track were lower when TSAS was active than when only the visual display of the GPS was used.

Tactile navigation cues have also been successfully trialled in the marine environment (**33**). One system uses the concept of a virtual corridor with tactor activation when the surface vessel or diver deviates from track as far as a 'wall' of the virtual corridor. In another application, the deviation of a craft's heading (in any of the four quadrants) from that required to reach a target waypoint was indicated by the location and frequency of tactor activation.

Cognitive assistance.

Paper **27** described components of a system that would monitor the pilot's functional state and flight parameters in order to detect any degradation of performance that would indicate excessive workload or diminution of cognitive function. On recognition of a problem, the system would provide assistance to the pilot or, if necessary, take over full control of the aircraft until the pilot was able to resume control. It is envisaged that the system will have three modules: 1) To monitor the status of the aircraft situation and outside environment, and to recommend actions. 2) To monitor the pilot's physiology and behaviour to provide an estimate of pilot state. 3) To monitor the mission plan and manage the interface to the pilot. The integrated output of these modules will provide cognitive assistance through adaptive automation and decision support. It will have the potential to cancel SD by effective real-time adaptive counter measures using flexible levels of autonomy governed by pilot-agreed plans. The authors were of the opinion that the implementation of such a system is technically feasible, but it is inchoate in so far it has yet to be implemented in hardware.

SD Causal Mechanisms

General

The role of the vestibular and visual sensory systems in the aetiology of SD are reasonably well understood and can be effectively modelled (**1**). Such models can also be employed in the analysis of SD accidents and for the reproduction of flight scenarios, that include the possible perceptions of the pilot, to aid investigators (**10**). However, the interaction of vestibular and cardiovascular responses in causing, or more likely potentiating, SD has not been explored in depth. The insentient pilot, because of G-induced loss of consciousness (GLOC) is, by definition, disorientated. The syndrome 'Almost loss of consciousness' (ALOC) is also induced by +Gz load and can impair cognitive function with the consequent degradation in perception and interpretation of spatial information. The experimental induction of ALOC by pulses of Z-axis acceleration (**48**) revealed the range of physical and emotional symptoms as well as cognitive deficits that could occur. These behavioural changes were associated with a fall in the level of cerebral tissue oxygenation, although they often persisted well into the post-exposure period when cerebral oxygenation had recovered.

Spatial disorientation on G-transition and on recovery from high rates of roll was discussed in paper **4**. Several factors were considered to be implicated: 1) The effect of intense vestibular stimulation causing a decrease in cerebral blood pressure with the consequent reduction in G-tolerance and increased likelihood of ALOC or GLOC. 2) Interference with vision by inappropriate vestibular nystagmus on recovery from the roll and loss of external visual references during the manoeuvre. 3) Illusory sensations of rotation on recovery.

Individuals who are motion sick not infrequently complain of dizziness that can be of sufficient intensity to constitute SD. The associated loss of well being and changes in behavioural state with impairment of cognitive function can, it was argued (**38, 43**), increase susceptibility to SD. Motion stimuli can induce drowsiness, the 'Sopite Syndrome', without frank motion sickness, and this may contribute to SD because of the attendant low level of behavioural arousal and diminished cue utilisation.

Conclusions and Recommendations

The Symposium provided a valued update about the prevalence of SD incidents and accidents within the Air Forces of several countries, and on the training aircrew receive to combat the problem. Existing collaborative work on these topics could profitably be extended to involve other countries. Standardisation of the collection of data on accidents and the criteria to be employed in the identification of SD as a primary or contributory cause of the accident would be advantageous.

In SD training, the demonstration of vestibular illusions should not overshadow the demonstration of visual illusions or instruction on the role of distraction and lack of crew co-ordination in the causing SD. There is also benefit in the demonstration of SD scenarios in a full-mission, flight simulator, preferably one having a good visual display and motion base.

Centrifuge experiments, which simulate aspects of the dynamic environment in manoeuvring agile aircraft, have found large individual differences in the SD induced. Further studies are needed to determine the variability of subjective responses to combined G_z/G_y and G_z/G_x in the relevant aircrew population. The benefit of centrifuge training to desensitise those aviators, who have strong illusions, merits assessment.

Tactile displays have been shown to provide intuitively useable cues for spatial orientation, navigation and other tasks in aerial, marine and terrestrial environments. There is evidence that tactile cues provided by relatively simple displays are processed within the central nervous system without making demands on higher level resources. Current work on the development of more complex tactile stimulators (*e.g*. one providing a sensation of movement) or of displays with a more complex coding (e.g. by increase in the number of tactors, or their vibration frequencies) should take care that the increase in information provide by a more complex display is not at the cost of placing an increased load on higher level processing and thereby vitiating one of the principal benefits of a tactile display.

Work on the feasibility of developing a system for the provision of cognitive assistance to the pilot, or even taking over control, should be continued. The system, as envisaged, has the potential to combat SD and prevent SD accidents, but there are considerable technological hurdles to be overcome, not least the development of a module to monitor reliably the pilot's physiology and behaviour in a non-invasive manner.

Modelling of sensory systems that subserve the perception of spatial orientation is of value in understanding causal mechanisms of SD and for the prediction of the sensations and control responses of a pilot in a SD accident. It is also useful in the design of control systems of simulator, motion platforms. More information is needed on inter-subject variability of responses to motion stimuli, in order to be able to substantiate statements about the likelihood of occurrence of a predicted response in an accident scenario.

Rigid inflatable craft should have better provision of cues, within an inverted hull, for the spatial location of the escape hatch. Crews should also have training in escape from an inverted craft, similar in principle to that given to helicopter aircrew.

Service medical officers should be made aware of the SD and other symptoms of the Motorists' Disorientation Syndrome and of the Exercise Induced Intolerance Syndrome, as these conditions should be considered, amongst many others, in the differential diagnosis of vertigo and SD.

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Spatial Disorientation – A Perspective

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Introduction

I am honoured to have been invited to give the keynote address to this symposium on spatial disorientation. Spatial disorientation (S.D.) is not a new problem in aviation and over the last 50 years it has been addressed on numerous occasions within the NATO community. Yet despite the increased understanding of the varied aetiology of S.D. and improvement in the display of information to the pilot to facilitate correct spatial orientation (S.O.), accidents, primarily attributable to S.D., continue to occur. Indeed, in the last decade the proportion of human error accidents in which S.D. was considered to be a primary or contributory cause of the mishaps has increased. This would appear to be due, at least in part, to the introduction of new technology, in particular night vision goggles, that has allowed flight operations in environmental conditions which previously were not possible.

In the presentations to follow there will be descriptions of new technologies and training techniques that should aid the maintenance of spatial orientation (S.O.) in flight and reduce the frequency of S.D. incidents and orientation error accidents. But these benefits are likely to be tempered by new challenges arising from flight in high performance agile aircraft and unattended aerial vehicles - UAVs. The human factors and aeromedical community also need to be cognisant of S.D. in virtual reality environments as well as in those piloting UAVs.

I would like to put this contemporary work in perspective - an historical perspective. I am, however, humbly aware that I will be a victim of perspectivism – that is knowledge of a subject is inevitably partial and is limited by the individual perspective from which it is viewed. My perspective has been acquired from the work I have done on SD and aspects of vestibular function since I joined the RAF Institute of Aviation Medicine in 1956. I have also been influenced by many of the people with whom I have worked, notably Fred Guedry – the doyen researcher in this field, who at the age of 80 is still active as is evidenced by the presence of his name on two of the papers being presented at this symposium.

Early History

When I began work at Farnborough the problem of S.D. had been known for more than 40 years, albeit not always by that name. Early in the history of powered flight it seems that the danger of flying without adequate visual cues – as when flying in fog or cloud – was not recognised. This is what Sir Geoffrey de Havilland wrote about his experiences when flying the RE1 biplane from Farnborough in 1913: " *Today it seems strange that the extreme dangers of flying in fog were not realised in the early days…….I have discussed this matter with other early pilots, and it seems to me that it was largely psychological – as long as one did not realise the danger, all was well, but when it was fully realised, due to an increasing number of fatal accidents, no one could fly through cloud without apprehension of losing control"* During WW1 the increasing number of accidents in which pilots lost control and came spinning out of clouds, led the medical authorities to institute tests of balance and vestibular function in the selection of aviators. They argued that, surely, the vestibular apparatus, which was known from the work of Ewald, Mach, Crum Brown and Barany, amongst others, to be the specialised sense organ for the preservation of balance and equilibrium on the ground, would be just as important, if not more so, in the flight environment. Major Isaac Jones of the US Army expressed contemporary opinion in an article published in the Journal of the American Medical Association in 1917 (Jones,1917):"*In order, therefore, to preserve that wonderful accuracy necessary in controlling such a delicate machine, he (the pilot) relies pre-eminently on his ear balance sense…. It is also highly probable that many an aviator has gone to his death because unknown to him, he did not possess a normal ear mechanism"*

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

The demonstration, by Jones et al. that a blindfolded deaf mute did not perceive aircraft attitude and motion as well as normal person without vision, was adduced as evidence for a requirement of normal vestibular function in potential aviators. This led to the use of the Barany rotation test in the medical selection of pilots. Applicants whose duration of post-rotational nystagmus after 10 turns in 20sec was less than 10sec and longer than 34sec were rejected. Jones' conclusion that the vestibular system is a reliable sensor of aircraft attitude and motion was widely accepted at the time, even though his paper contains such statements as " *…on the second flight the pilot made no fundamental error, simply mistaking right and left horizontal slow turns*". However, experiments carried out in-flight by other investigators towards the end of WW1 demonstrated that in the absence of vision man realy did not have sensory systems capable of controlling such a "*delicate machine*". Thus O'Reilly and MacKechnie (1920) writing in the Canadian Medical Monthly reported:"*…certain experienced RAF pilots were taken into the air, blindfolded and given control. In every case these pilots were able to control their machines for only a short distance even on straight flights. On attempting turns or even the simplest manoeuvre they stalled their machines, slide slipped or nose dived while thus flying unaided by their visual sense.*"

Further doubt was shed on the postulated importance of vestibular testing by Parsons and Segar who found no correlation between performance on the Barany test and flying ability. Indeed, experienced pilots were found, on average, to have a shorter duration of post-rotatory nystagmus than those with less flight experience -- evidence of vestibular habituation brought about by exposure to aircraft motion.

The clearest rebuttal of importance of the vestibular system for orientation in flight came from the reasoned observations and experiments of a certain Dr Wulfften Palthe who in 1922, when his paper entitled "Function of the deeper sensibility and of the vestibular organs in flying" was published in Acta Otolaryngologica, who was head of the medical service of the Royal Netherlands Airforce with the rank of Flight Lieutenant. I make special mention of this article because it was the first to describe clearly many of the illusory perceptions that occur in flight which came to be categorised as spatial disorientation. Wulfften Palthe clearly appreciated that the aviator's failure to perceive turns and changes in attitude was due to the fact that the motion of the aircraft was below sensory threshold. He described the sensations engendered by looping and rolling manoeuvres, the failure to perceive bank in a co-ordinated turn – now called a somatogravic illusion. He gave a clear account of the false sensation of turning – the vertigo, or somatogyral illusion – on recovery from spinning, and how this could lead to the pilot re-entering the spin. He also provided the first description of the vertigo induced by a change in atmospheric pressure on ascent - what we now call pressure or alternobaric vertigo. Wulfften Palthe concluded:" *It is very difficult to imagine, when one sees an aeroplane in the air standing almost vertically on its side…..or making rather rapid turning movements, that the occupants perceive nothing of it when their sense of sight is eliminated. …… In view of all this I consider it proved that the vestibular organ is of no special significance to the aviator, that is it does not enable him to steer an aeroplane in cloud or mist. This does not mean that the vestibular organ is of no importance at all to the aviator. It is just as important to him as a person on the ground, but neither quantitatively or qualitatively does the labyrinth play an exceptional role. There is, however, one exception and that is when, owing to some reason or other, it causes vertigo, which may have much more disastrous consequences for the aviator than for the person on the ground*"

Before the end of the First World War in 1918 the need was recognised for the pilot to have some form of instrument display of aircraft attitude and motion when there were no external visual cues for orientation, as when flying in cloud or at night. In the early 1920s a gyroscopic turn indicator developed by Sperry in the USA from a device originally designed for marine use, was introduced. However it was not until 1929 that a gyroscopic artificial horizon – not dissimilar in appearance to those in use today – was flown (Ocker,1930). A series of landings and take-offs using these, so called, blind flying instruments demonstrated their utility and the first solo, blind flight took place in 1932. In theory these flight instruments allowed correct control of the aircraft to be maintained in the absence of external orientational cues. However, their introduction did not prevent accidents to aircraft flying in cloud, fog etc., because some pilots mistrusted the instruments. They were more ready to base their control of the aircraft on their own sensations than on the instruments. Consequently they lost control and, if it was not regained once out of cloud, then an accident was inevitable. Even with rigorous training in instrument flight and emphasis on the need to ignore 'seat of the pants' sensations, accidents continued to occur in conditions of poor visibility.

Most of the papers published in the 1930s confirmed or elaborated on the observations of Wulfften Palthe. Mention should, however, be made to the writings of Schubert (1931) who described the effects of head movement in a turning aircraft due to Coriolis or cross-coupled stimulation of the semicircular canals. He also explained how the plane of the vertigo induced on recovery from a spin, could change when the head was moved after the aircraft had stopped spinning – the Purkinje phenomenon. During WW2 night take-off accidents were investigated by Collar (1946). He showed from an analysis of the flight trajectory that the pilot would experience a near constant X axis acceleration and an erroneously sensed nose-up attitude, even though the aircraft had bunted and was about to impact the ground. This was a clear description of what we now call the somatogravic illusion – an illusion that, even today, continues to be a killer in both military and general aviation.

Post WW2 Research

The first detailed survey of aviators' experience of spatial disorientation and other perceptual disturbances in flight was carried out by Vinacke in the US Navy shortly after the end of WW2 in 1945. Further questionnaire surveys by Clark and Graybiel in the USA and Melvill Jones in the UK, published in 1956 and 1957 respectively, yielded a reasonably comprehensive picture of the various types of illusory perceptions experienced by aviators and the multifactorial aetiology of S.D. or aviator's vertigo as it was commonly, if incorrectly called in those days. It was also in the mid 1950s that the first analysis of accidents attributable to S.D. was carried out by Nutall and Sanford (1956).

Thus in 1957, when I was beginning to learn about S.D., there was already a substantial amount of information available on the topic. It was apparent that the illusions, the erroneous perceptions, occurring in flight were not just confined to errors in the perception of aircraft attitude and motion but also to errors in the perception of distance and of the spatial relationships of the aviator's own body to his surroundings. Control system models of the human operator were a contemporary fashion and one produced at that time had heuristic value in the identification of key elements in the aetiology of S.D.(Fig.1)

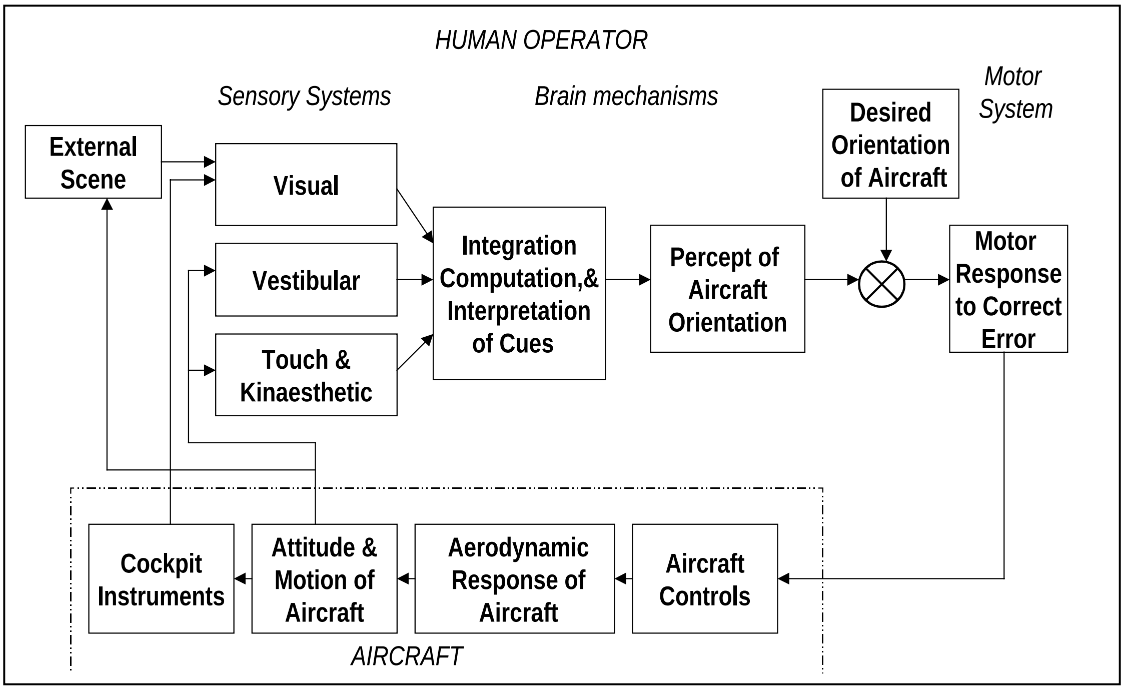

Figure 1, Block diagram of closed-loop, control of aircraft spatial orientation. The pilot receives feedback from vestibular and kinaesthetic receptors, stimulated by angular and linear accelerations, that are phase advanced on the velocity and displacement of visual cues.

In the 60s and 70s I was involved in carrying out tests of vestibular function on all aircrew who were referred to the RAF neuropsychiatrist because of S.D. This work did show that, as a group, there was slightly more, and marginally significant, vestibular asymmetry in those aircrew with S.D. than in a control group. In some cases the demonstration of an asymmetry in yaw or roll axis sensation cupulograms explained the illusion experienced by the pilot (Benson,1973a). Quite frequently this explanation could allay the anxiety, the neurosis, that often was responsible for the recurrence of the illusion in specific flight conditions (Benson,1973b). From this clinical work, coupled with the study of incidents and accidents in which S.D. was thought to be implicated, as well as from discussions with aircrew and flight medical officers, it became clear that on most occasions in which an aviator had an erroneous perception – an illusion – that fell within the definition of S.D., correct control of the aircraft was maintained and the flight continued safely. Relatively rare were those incidents in which the pilot did not realise that his control of the aircraft was based on an erroneous percept of its orientation. Unless the error was recognised, with sufficient time and sufficient altitude for proper control to be established, an accident would be the almost inevitable consequence. These observations led to a classification of S.D. into two categories: Type 1 – Unrecognised S.D. –, and Type 2 – Recognised S.D. –, a classification that has been widely adopted. Although in the USA and Canada researchers have added a Type 3 S.D. to identify those incidents, such as the 'Giant Hand' phenomenon, in which there was severe disorientation stress, degradation of performance, even incapacitation. In these rare events the aviator is generally aware of his or her difficulty so I consider it to be an expression of an extreme form of a Type 2 S.D.

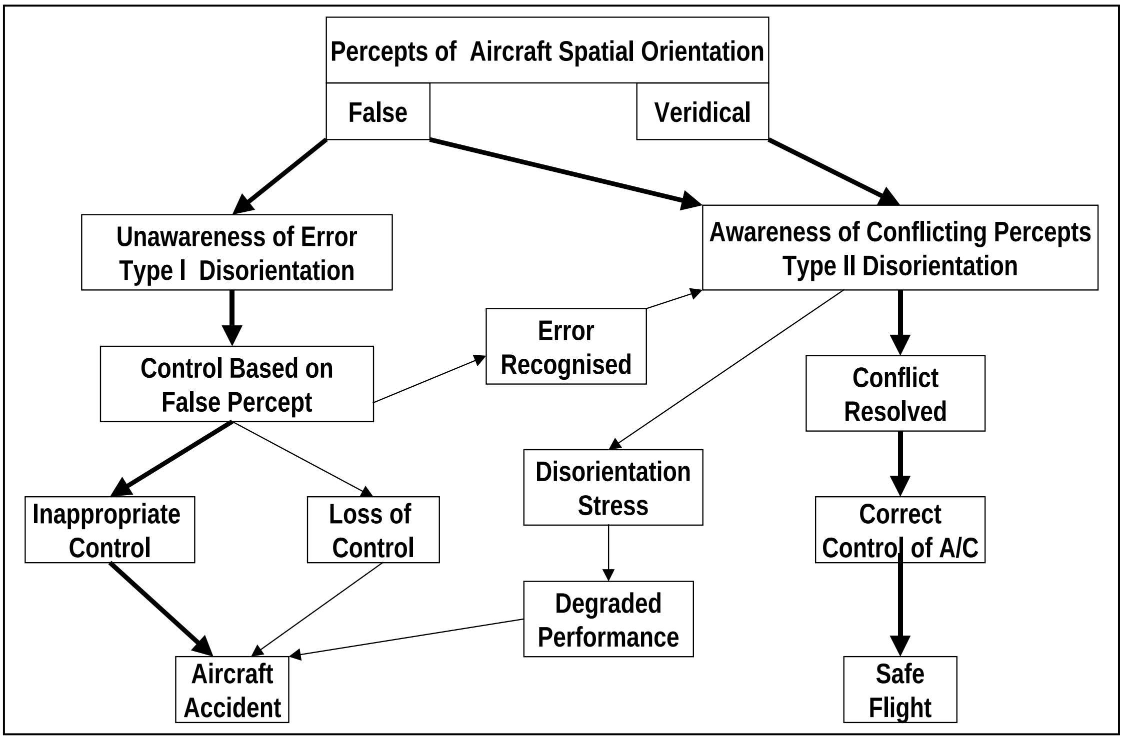

Figure 2. Diagramatic representation of how Type I and Type II spatial disorientation can effect the pilot's control of the aircraft

In the 1970s there was the first description by Gilson, Guedry, Hixon & Niven (1973) of the G-Excess illusion, in which illusory perceptions of attitude were induced when head movements were made in an aircraft pulling G at an angular rate insufficient to cause appreciable cross-coupled or Coriolis stimulation of the semicircular canals. They described a dynamic component of the illusion during the head movement and a static component when the head was maintained in the deviated position. An important conceptual advance in the understanding of the mechanisms of spatial orientation was also made in the 1970s by Leibowitz.and Dichgans(1980). They drew a clear distinction between the roles of what they termed the focal and ambient visual systems in spatial orientation. The ambient system is innervated by afferents from the greater part of the retina subserving the peripheral visual field and is responsible for spatial orientation when a structured visual scene is present.As illustrated by Fig.3, orientational cues are processed by the ambient visual system when flying in VMC (visual meteorological conditions) using external visual cues, and by the focal visual system when flying by instruments in IMC (instrument meteorological conditions).

The past 20 years has seen a consolidation of our knowledge about the differing psychophysiological mechanisms involved in S.D. and of the many factors that are of aetiological importance. I need not dwell on the causes of S.D., as this is the topic of first session of this symposium. Also the past 20 years has seen the introduction of the term 'situational awareness', and its antonym 'loss of situational awareness'. Situational awareness refers to the aviator's global current percept of "key elements in the flight environment", and how they may change in the near future. Key elements include, navigation, weather, tactics, nature of threats and defence, aircraft systems and spatial orientation. Unfortunately, some authors have used the term loss of situational awareness as a synonym for S.D. This is incorrect; an aviator with S.D. is by definition suffering from loss of situational awareness, but not all instances in which there is loss of situational awareness is the aviator disorientated. Taxonomically, S.D. already covers a wide range of perceptual errors; so many factors fall within the scope of ''loss of situational awareness' that the utility of the term is compromised.

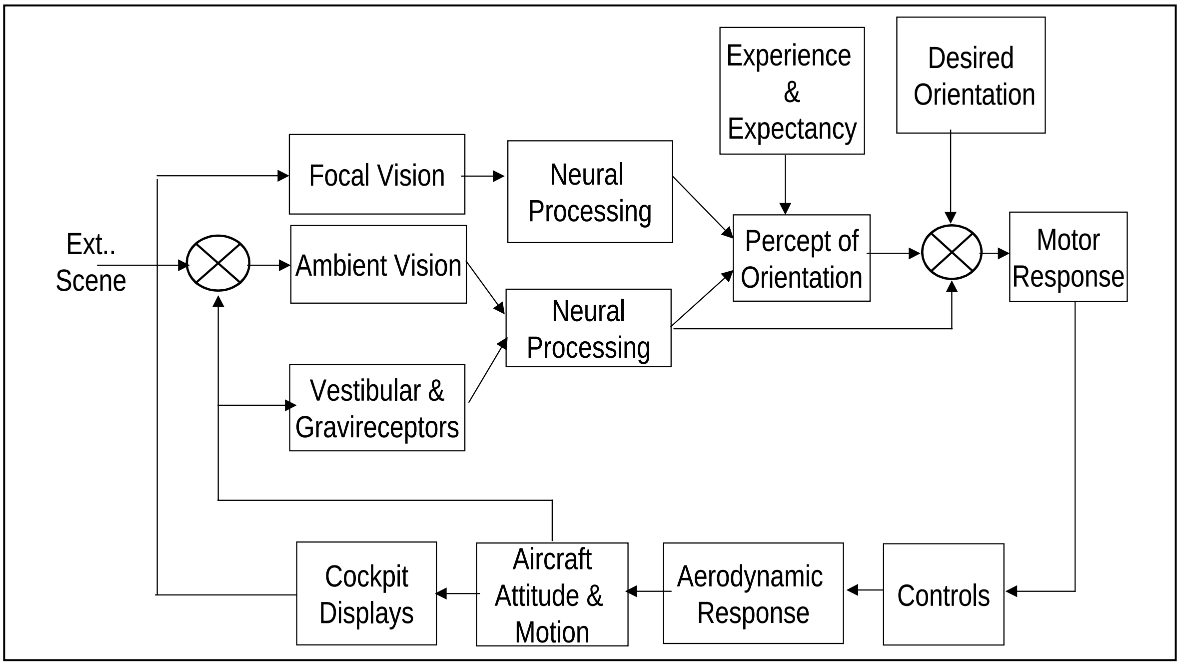

Figure 3. Block diagram of closed-loop control of aircraft spatial orientation to illustrate the separate functions of the focal and ambient visual systems. It is suggested that inputs from the ambient visual and vestibular receptors share a common pathway and neural centre for the processing of afferent information, and that its output can influence control responses without conscious intervention –although accessible to conscious perception.

Nearly 50 years ago Nutall and Sanford (1959), in drawing conclusions from their seminal study of S.D. accidents, wrote: " *If accidents due to "vertigo" continue to be a significant cause of attrition amongst fully trained and experienced pilots, then more attention should be focused upon the problem of spatial orientation and the possibility that the present indoctrination, training and proficiency maintenance are inadequate or that existing instrumental means of maintaining orientation in flight do not meet human requirements under all circumstances*." What Nutall and Sanford wrote in 1956 (paper not published in open press until 1959) is no less true today. Of course over the years there have been some improvements in the training of aircrew and there have been extensive developments in displays, not only in head down displays (HDD) but also in head-up (HUD) and, more recently, head-mounted displays (HMD). Unfortunately some of these advances have increased the likelihood of S.D. For example, the poor reliability of early HUDs and its poor symbology for recovery from unusual attitudes, combined with the relegation of the artificial horizon to an off-centre position in the instrument panel, would appear to have been responsible for a number of S.D. incidents in early Harrier aircraft of the RAF. The introduction of night vision goggles (NVGs) and forward-looking infrared (FLIR) displays whilst increasing operational capability has been at the cost of an increase in S.D. incidents and accidents, particularly in helicopter operations. Currently the representation of aircraft orientation and flight trajectory on HMDs during off bore-sight head movements is not without problems.

Prophylaxis

What then can be done to prevent, or at least decrease the number of, orientation error accidents and the decrement in operational efficiency due to S.D.? Prophylaxis may be summarised under three headings: 1) Presentation of information on aircraft orientation and to aid recovery from UAs, 2) Selection and training, and 3) Flight control systems.

It may be argued that displays should emulate innate orientational mechanisms and provide cues to the aviator's ambient visual system. The Malcom Horizon – a beam of light projected across the width of the cockpit – provided an ambient visual cue. It worked well in roll but in common with many conventional attitude instrument it displayed changes in pitch attitude at a 1:1 ratio only over a narrow range and hence did not facilitate recovery from UAs. Wide field of view head mounted displays have the potential to provide effective ambient cue although they are not without problems, such as how the configuration of the display should change with off bore sight head movement, pitch ladder scaling, and symbology for UA recovery. Unfortunately time does not permit me to review the many human factors aspects in the design of displays for spatial orientation and UA recovery.

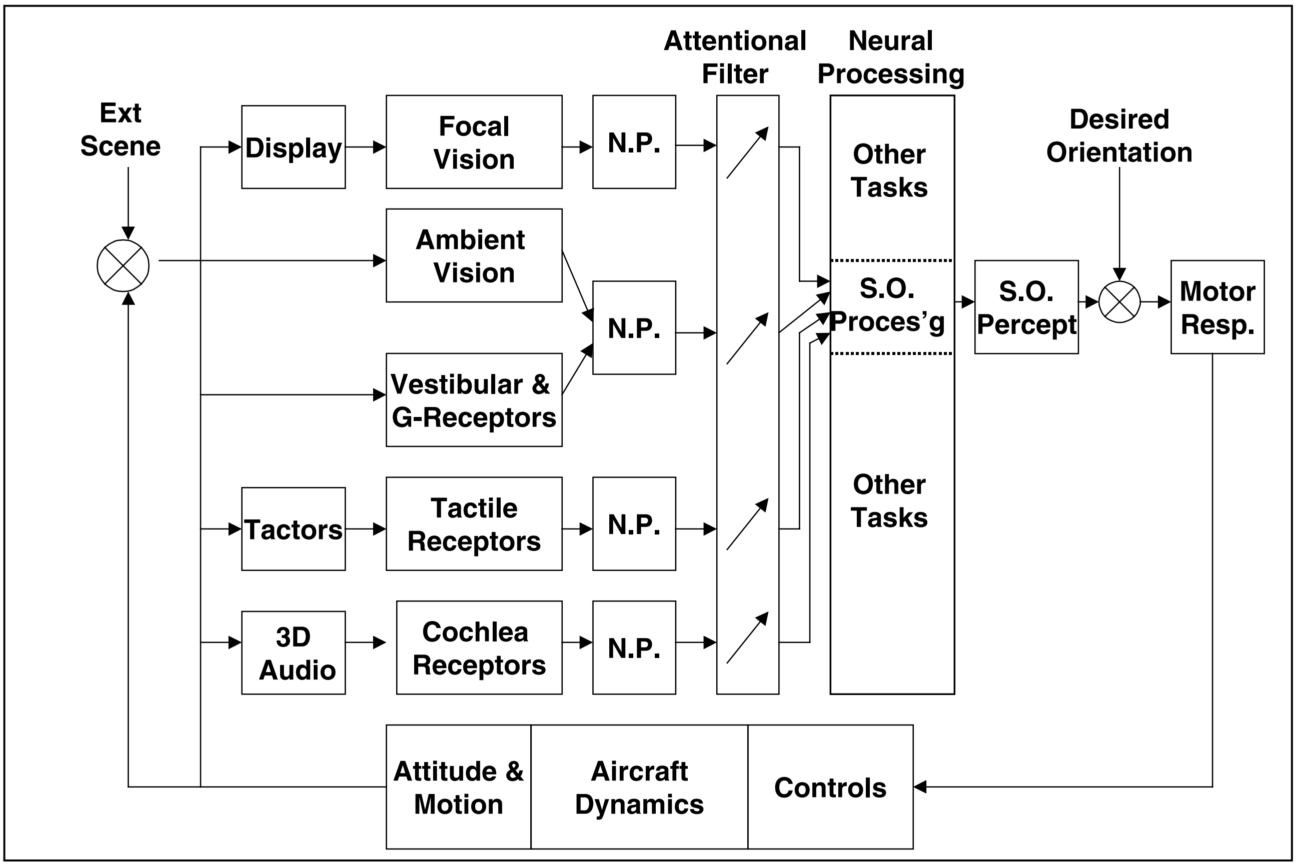

Figure 4. Block diagram of closed-loop control of aircraft spatial orientation (S.O.) to illustrate possible pathways for the neural processing (N.P.) of afferent sensory information, and the presence of a filter that restricts conscious access in conditions of high task load (coning of attention)

With the heavy demands placed on the aviator's visual sensory system in the modern cockpit, attention has been given to the use of other sensory systems for the presentation of information to the pilot. The development of 3D audio displays allows spatial information to be given to the aviator. Experimentally, the use of 3D audio cues has been shown to aid the localisation of ground or aerial threats and for facilitating target acquisition, thus it enhances situational awareness. The value of 3D audio for spatial orientation is less certain. An auditory signal is not a powerful orientational cue. A sound source, fixed with respect to the observer, will not suppress an illusory sensation of turning, such as occurs on stopping from sustained rotation. Localisation of the sound source may be slightly displaced in the direction of the perceived turn and appear to rotate with the observer in accord with the illusory sensation of bodily rotation – the audiogyral illusion. Furthermore, with 3D audio, front/back confusions are relatively common.

The haptic sensory system can also be used as a channel for the provision of information on spatial orientation. Of recent years this has been implemented by Rupert et al. of the US Navy by the use of an array of tactile stimulators (tactors) distributed about the torso in a vest or waistcoat like garment (Rupert,2000). The pattern of tactor activation was used to indicate the direction of the gravitational vertical and hence aircraft attitude. This display permitted successful 'Blind Flight' without a conventional attitude indicator. Tactor activation may also be coded for vertical and/or horizontal velocity and in helicopter simulations was shown to minimise drift during hovering. Tactors can also be used, like acoustic displays, to indicate the position of ground or airborne threats. It has been suggested that the processing of haptic cues for spatial orientation are mediated, like ambient visual cues, through primitive neural systems in which information is processed at a subconscious level. Thus their use may release neural resources for other tasks and in so doing enhance veridical perception of aircraft orientation, situational awareness, and operational effectiveness.

Selection and Training

The importance of selection and training of aircrew has long been recognised and selection and training relevant to S.D. is no exception. Normal equilibratory function and the absence of vestibular disorder is mandatory in the medical selection of aircrew, but there is no need for special tests of vestibular function, such as the caloric test and nystagmography, to be carried out. The place for special tests of vestibular function is in the investigation of aviators who come under medical care because of a S.D. problem.

In regard to training, some have argued that aviators learn about S.D. and how to cope with it during the course of instrument flying training. It cannot be denied that proficiency in IMC flight and the ability to recover from UAs is of primary importance in preventing orientation error accidents. But experience gained during training and subsequent operational flight can be limited and it does not, necessarily, give the aviator an overview of the varied manifestations of S.D. nor of its many causal factors.

Most now accept that flight experience should be complemented by specific instruction about S.D. as well as by a demonstration in which the student aviator experiences some of the perceptual errors that can be engendered by the unfamiliar motion and visual stimuli of the flight environment. Such a demonstration of the fallibility of human perception is most convincingly achieved in actual flight, and effective protocols have been developed for in-flight demonstration of S.D.. However, considerations of cost and flight safety have led to the much greater use of ground-based S.D. demonstrators. These range in complexity from a simple turntable to a short arm centrifuge with gimballed cab and visual displays capable of reproducing many of the illusions and flight scenarios in which S.D can occur. There is clearly pedagogical benefit in the deployment of an advanced S.D. demonstrator that is, in effect, a dynamic flight simulator. Less certain is the benefit to a student pilot of repeated sorties in such a device where the objective is to develop proficiency in coping with S.D. in specific flight scenarios. But many of these are simulated by motion of the device that is substantially different from that of the actual aircraft. Is there not a danger of negative transfer of training, insofar as procedures developed during repeated exposure in the S.D. trainer may be inappropriate in actual flight?

Proof of the benefit of any change in S.D. training is difficult to obtain. It is of course reassuring to have favourable reports from the students, but more meaningful is a reduction in the number of accidents attributed to S.D. Unfortunately, accident rates are a noisy statistic especially when the criteria for deciding if S.D. is a relevant factor are not clear-cut and are amenable to individual interpretation. In addition, S.D. accidents are infrequent events, so data has to be accumulated over several years, a period in which operational requirements, as well as aircraft type and fit are unlikely to be static. An alternative approach would be to survey the incidence of critical S.D. incidents in sample aircrew populations. This too is not without criticism: For are not aircrew who are knowledgeable about S.D. more likely to report S.D. incidents than those who are poorly informed about the topic?

Automated Control Systems and Pilot Assistance

Even when the pilot is disorientated, orientation error accidents may be prevented by a flight control system that in critical situations takes control away from the pilot and puts the aircraft into a safe flight trajectory. Effective ground collision avoidance systems (GCAS) have been developed that apparently work well over terrain whose topography is mapped and stored in the aircraft's computer, and there is sufficient time for recovery to take place. Control systems to provide automatic recovery from UAs on initiation by the pilot have also been developed for contemporary high performance aircraft.

Unattended Aerial Vehicles (UAVs)

With the advent of highly agile aircraft having a performance envelope greater than human tolerance and capability, the logical next step is to for the human controller of such vehicles to be located outside the vehicle – either on the ground or in another less agile aircraft. UAVs that require only the setting of waypoints and limited dynamic control are unlikely to present a S.D. problem. In contrast where the exteriorised 'pilot' has to control a highly manoeuvrable vehicle, such as a Combat UAV, from information provided by optical and other sensors on the vehicle, there is considerable potential for pilot disorientation and loss of control. Relevant factors are the restricted angle of view of the vehicle's forward looking sensors, and lags in the display of information from the vehicle. Furthermore, the 'pilot' lacks mechanical motion stimuli to his/her body such as provide the dynamic, phase advanced, cues which aid hands-on control in conventional high performance aircraft.

Conclusion

So in conclusion: In this short talk I have covered some aspects of the history and the development of concepts about spatial disorientation in flight. It is apparent, however, that despite an understanding of the multiple aetiology of S.D., and the efforts made to combat the problem S.D. is still with us. It is, I fear, likely to remain so, so long as there is a human in the control loop. I am not sanguine that S.D. and accidents caused by it will ever be entirely prevented. Nevertheless, I am more hopeful that techniques, procedures and training - some aspects of which will feature in the papers and posters to be presented over the next three days – will be of benefit and will reduce the number of accidents, save lives, and enhance operational effectiveness.

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The Cause of Spatial Disorientation

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SUMMARY

We here present a model including visual-vestibular interactions describing the basic properties of the human spatial orientation system. It hence also explains and describes spatial *dis*orientation. The model indicates that spatial orientation should at least be characterised by four variables: linear acceleration and velocity, angular velocity, and attitude. Perception of the latter is part of the subjective vertical. Due to visual-vestibular interactions at different levels, these variables are partly independent, and may therefore behave differently. This is demonstrated by two examples concerning a takeoff. A moderate takeoff is simulated by means of a Stewart platform, a high G-load takeoff, like the catapult launch on an aircraft carrier, by a centrifuge. Model predictions are shown and concisely discussed, with further reference to previous papers on this matter. This elaboration, and the notice that we normally (in case of self propelled motion) need a sense of self motion for self control of body motion, leads us to the following conclusion: the main cause of spatial *dis*orientation is the indistinguishability of accelerations due to motion (i.e. inertial accelerations) and those due to gravity. This problem is further enhanced by a limited range of (near) perfection of our visual and vestibular sensors. Unfortunately, the high performance military flight environment is definitely out of that range.

INTRODUCTION

If we had evolved in space, we would not have encountered problems with spatial disorientation (SD) as we have on earth. In space, i.e. in weightlessness, the only accelerations met are those due to motion (inertia), and our vestibular system is capable of estimating these motions adequately. On earth, however, we are also faced with gravity (masses attract each other), and by Newton's second law this gives rise to the gravitational acceleration. The problem we have on earth is that both accelerations are physically different but indistinguishable (Einstein's equivalence principle). As a consequence, there are no sensors that can make this difference, and this also holds for our vestibular apparatus (see below). To control our motion, however, we should know how well an intended motion has finally been achieved. The most simple way to describe this control is by means of a simple feed back loop as sketched in Fig. 1.

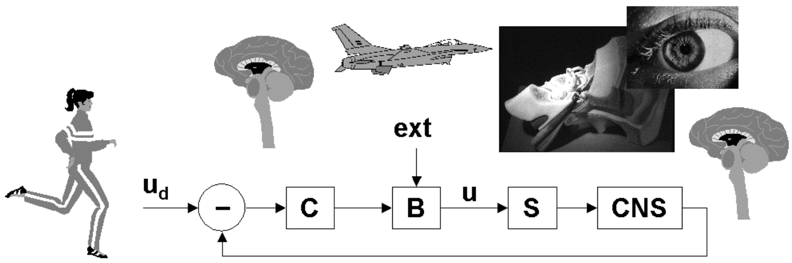

Fig. 1. Simplified representation of the human motion control loop. A desired body state ($\mathbf{u}_d$), directs a controller (C) within the central nervous system (CNS) generating motor commands that drive the muscles in the body (B). The body can also be moved by external sources like that of an aircraft. The actual state of the body (**u**) is registered by (among other things) the vestibular apparatus and the visual system, which signals are processed by the CNS for comparison with the desired body state.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

Hence, for the purpose of motion control, inertial accelerations should be separated from gravitational accelerations, the latter determining our sense of attitude, and our sense of motion should be exact. As will be illustrated by the following examples, these conditions are not always met.

If, for example, we are rotated on and about an earth vertical axis with a constant velocity, our sense of (angular) motion will vanish within tens of seconds (Fig. 2). If we are rotated about an earth horizontal axis (Fig. 3), this also happens, but, because we then also "feel" a change of gravity with respect to our body, we interpret this motion then as if we are moved like a gondola on a Ferris wheel (Mayne, 1974; Mittelstaedt et al., 1989). Another important phenomenon concerns the somatogravic illusion (Graybiel et al., 1947; see Fig. 4). This illusion refers to a perception of tilt when only submitted to a linear acceleration. It has also been shown that this illusory perception of tilt only comes forth gradually within a period of (tens of) seconds. Graybiel and Clark (1965) subjected several subjects to a centripetal acceleration in a centrifuge to show this (see Figs. 5 and 6).

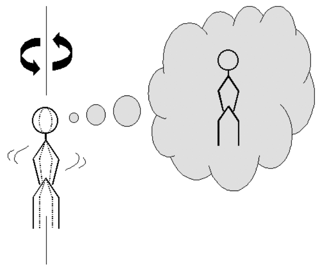

Fig. 2. After several tens of seconds of constant angular velocity about an earth vertical axis, motion perception has returned to a stand still.

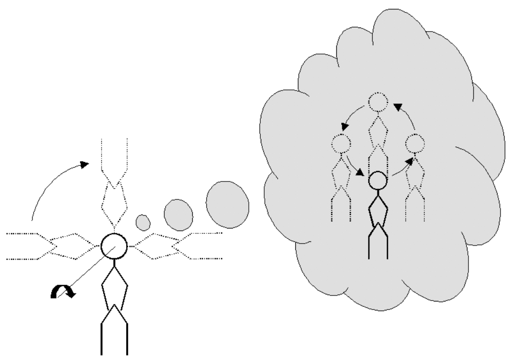

Fig. 3. A rotation about an earth horizontal axis results in a disappearance of angular motion sensation too, but here a Ferris wheel like motion results due to the relative motion of gravity about the subject.

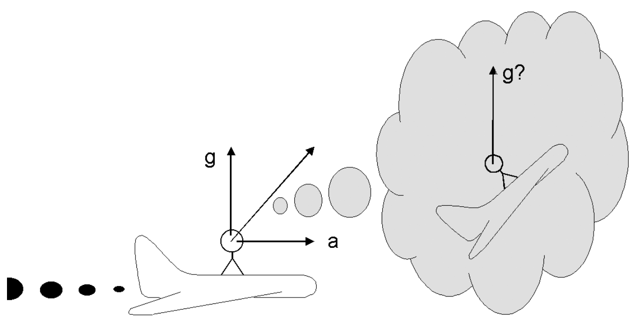

Fig. 4. Somatogravic effect. During linear horizontal acceleration (**a**), the direction of the resultant acceleration is interpreted as that of gravity (**g**), resulting in a sensation of tilt.

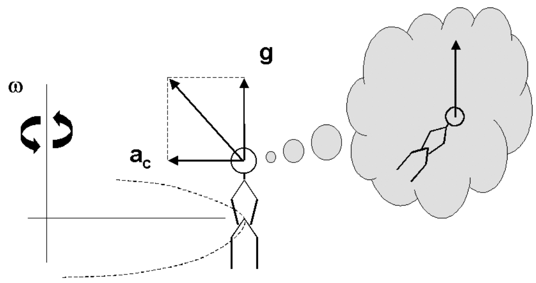

Fig. 5. Somatogravic effect. During centrifugation a centripetal linear acceleration $a_c = \omega^2 r$, with r the radius of the centrifuge, can be exerted to a subject for periods of time, much longer than induced by mere translation. Also in this case will subjects feel tilted, like in Fig. 4.

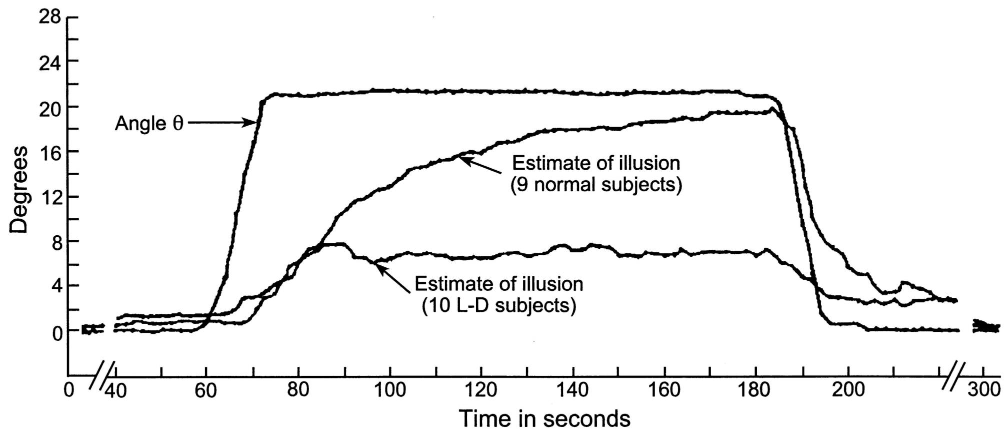

Fig. 6. Average estimated angle of tilt (θ) as observed by 9 normal subjects and 10 labyrinthine defective (L-D subjects), experiencing a centripetal acceleration of approximately 0.4g from. t=±60 to t=±185 s (after Graybiel & Clark, 1965).

Fortunately, there is some redundancy of information normally present, of which the visual cues are most important. We can also "see" what is up and what is down. Trees and houses should (normally) be upright, and the horizon horizontal. In addition there are somatosensory (pressure) cues, sometimes auditory cues, and cognition is at stake as well. This makes the description and explanation of spatial (dis)orientation a complicated matter, and we will, for the sake of simplicity, confine this paper to the two most important, that is to the vestibular and the visual subsystems.

First, some basics with respect to motion and attitude will be dealt with, followed by a theoretical framework that will serve the purpose of elaborating a model that may mathematically describe spatial orientation and motion perception. This model is built on knowledge of the vestibular apparatus and the subsequent processing of its afferents by our central nervous system (CNS). A most simple description will be used representing the processing of visual cues. Visual-vestibular interactions finally result in the (predicted) perceived motion and attitude. We have previously performed a series of flight simulator takeoff experiments using a Stewart platform, where experienced pilots judged the motions of different motion filter settings (Groen et al., 2001). As an example of the use of the currently presented model, we will simulate these simulator motions, in addition to those of a real takeoff, to explain the differences observed. A similar set of calculations will be presented concerning a catapult launch that can be simulated by use of a centrifuge. Because certain parts of the concept presented here have been published previously (Bos et al, 2001; Bos & Bles, 2002), we will only present the main flow of thoughts resulting in the final model, without focusing on details.

BASICS

Inertia and gravity

If we are moved in space, there are only six degrees of freedom (DoF) to be dealt with. We can be translated, giving rise to a change in position or velocity, and this may be characterised by the linear acceleration $\mathbf{a} = d^2\mathbf{x}/dt^2$, a vector with three components along three (orthogonal) axes. A rotation may additionally change the orientation, and this can be characterised by a three component angular velocity vector $\boldsymbol{\omega}$. Within each of our inner ears there are three more or less orthogonal semicircular canals (SCC), filled with fluid (endolymphe), which fluid will lag the head due to inertia. A piston-like valve (culupa) detects this flow of fluid, and signals the head rotation. Due to friction and the fact that the cupulae are fixed to the head, the fluid flow is damped, such that the neural canal signals are proportional to a high pass filtered angular velocity signal (e.g. van Egmond et al., 1949; Robinson, 1977). This implies that the SCC are insensitive to constant angular head velocity, and this is just what causes the illusions shown in Figs. 2 and 3.

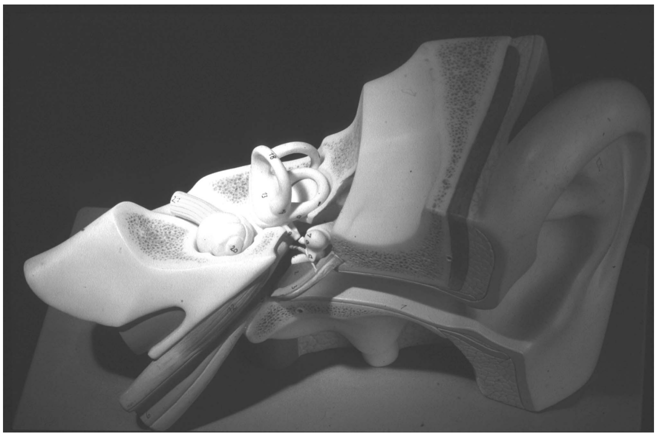

Fig. 7. A set of three semi-circular canals detect angular motion within each inner ear. Within the sac closing the three loops, additional hair cell layers with crystals on top (the otoliths) detect linear acceleration (see Fig. 8).

Within the sac connecting the canals, there are two layers of heir cells with crystals on top (the otoliths, see Fig. 8, which crystals have a higher specific density than the surrounding matter, such that these will lag due to inertia too, here to linear motion ($\mathbf{a} = d^2\mathbf{x}/dt^2$). However, these otoliths will also be attracted by gravity on earth (see Fg. 9, and they will also signal proportional to gravity ($\mathbf{g} = \mathbf{F}_g/m$). Therefore, also these otolithic sensors are not capable of discerning inertial from gravitational accelerations. This results in 9 DoF that have to be dealt with on earth (i.e. 3 inertial acceleration components, 3 gravity components, and 3 angular velocity components). For the remainder we assume that the otoliths transduce the resultant acceleration, or specific force, near perfection (e.g. Merfeld et al., 1993), i.e. their output is proportional to $\mathbf{f} = \mathbf{a} + \mathbf{g}$.

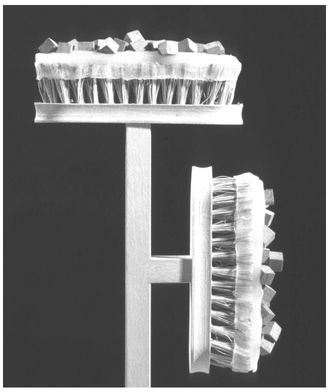

Fig. 8. A craftsman's impression of the otoliths.

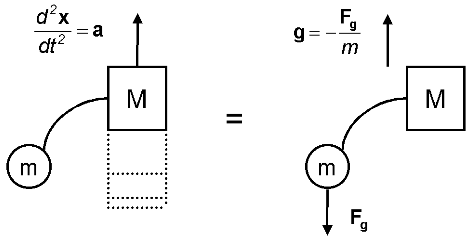

Fig. 9. Schematic representation of an otolithic crystal with mass m, connected by a hair functioning as a leaf spring to the body with mass M. If in space a force is exerted to the mass M, it will be moved with an acceleration a =d^2**x**/dt^2 = F/M. Due to inertia, the otolith mass m "wants" to remain in place, but it is dragged via the spring by M upwards, finally resulting a steady state condition that is equal to a condition of rest on earth, where the mass m is attracted by gravity. As a consequence, the gravitational acceleration should be directed opposite to the gravitational force vector.

As stated in the introduction, the accelerations due to motion (inertia) en due to gravity are indistinguishable, and if we would not discern gravity as such, we might feel like an astronaut within five minutes ($\Delta x = \iint g dt^2 = ½gt^2 \approx 440$ km, with $g = 9.81$ m/s^2 and $\Delta t = 300$ s). Obviously we do not feel this, and apparently our CNS does do something to the otolith afferents to make the distinction. Another example includes tilt. When tilted on earth, the gravitational acceleration may be exactly equal to the resultant of gravity and an acceleration forward and slightly downward (see Fig. 10) In the first example, some CNS-processing on otolith afferents only is requested, while in the second example, angular information from the SCC may aid in the solution to estimate motion and gravity. How this function of the CNS may be described mathematically is summarised in the next section on a spatial orientation model.

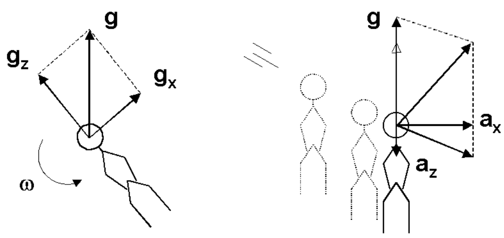

Fig. 10. The gravitational acceleration during tilt may be equal to the resultant of the gravitational and an acceleration forward and slightly downward.

A SPATIAL ORIENTATION MODEL

Vestibular function

To know inertial acceleration **a** (i.e. due to motion), the gravitational acceleration **g** should be subtracted from the gravito-inertial acceleration, or specific force **f**: **a** = **f** – **g**. However, we "measure" **f** with respect to the head, while **g** is earth fixed, and we should therefore calculate

$$\mathbf{a}_e = \mathrm{R}_\omega(\mathbf{f}_h) - \mathbf{g}_e. \quad (1)$$

with the indexes *e* and *h* referring to earth and head, respectively, and ω indicating that the rotation matrix is determined by the angular velocity as sensed by the SCC, for example. This, however, is only solvable if $\boldsymbol{\omega}$ and **g** are known exactly. In the previous section, however, we already showed that $\boldsymbol{\omega}$ is *not* known exactly, especially not during constant angular velocity. Moreover, there is no way to know **g** exactly. For we do not consider it a realistic option that gravity, both with its direction and magnitude, is known a priori, i.e. determined genetically, it should be estimated during life. One solution for this estimation has been given by Mayne (1974), who suggested a low pass filter to operate on otolith afferents. Because gravity is constant in an earth fixed frame of reference, while accelerations due to self propelled motion are variable, this indeed makes sense (see Fig. 11). Moreover, the temporal behaviour of the somatogravic effect as shown in Fig. 6 can also be explained by such a filter.

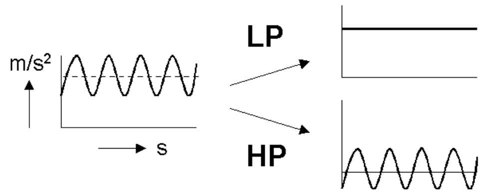

Fig. 11. Accelerations experienced during self propelled motion are composed of a variable component due to self motion and a constant offset due to gravity (Mayne, 1974). These components can be separated by means of a low pass (LP) and a high pass (HP) filter.

When also angular motions are reckoned next, the process of estimating both the gravitational component and the inertial acceleration, can be summarised as in Fig. 12.

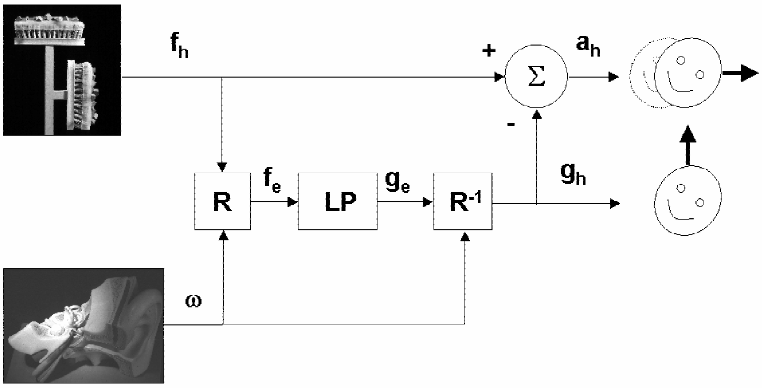

Fig. 12. Vestibular based spatial orientation model (after Bles & de Graaf, 1993). In the center of the model is a low pass filter (LP) operating in an earth fixed frame of reference. To obtain earth referenced components of the specific force ($\mathbf{f}_e$) as sensed by the otoliths, canal information ($\boldsymbol{\omega}$) is used to rotate(R) the head referenced vector ($\mathbf{f}_h$). Because the estimate of gravity ($\mathbf{g}_h$) finally is given with respect to the head, an inverse rotation (R^{-1}) is needed to accomplish this. In this model, motion perception is realised by the inverse of the gravity perception, i.e. $\mathbf{a}_h = \mathbf{f}_h - \mathbf{g}_h$.

Previously (Bos & Bles, 2002), we have shown that the mathematical equivalent of this model is given by

$$\frac{d\mathbf{g}}{dt} = \frac{\mathbf{f} - \mathbf{g}}{\tau} - \boldsymbol{\omega} \times \mathbf{g}\,. \tag{2}$$

where we have omitted the head referencing index. In fact, this description is the three dimensional equivalent of the two-dimensional model proposed by Mayne (1974).

Visual-vestibular interactions

Normally, we can also see how we move and how we are oriented in space, relative to other objects, or specifically relative to earth. This section will describe how these visual signals interact with the vestibular signals as described in the previous section. There are, however, many processes involved in visual perception, why this can not be described by one single interaction. First, retinal receptors should transduce the light quanta into appropriate action potentials, which involves photo-chemical processes. These neural signals next have to be transported to those parts of the brain that process them to result in perceptual responses. These processes are therefore relatively slow. Moreover, eye, head, and body movements are involved to acquire stable retinal images, and we also make inferences about our self motion based on visual information (vection, see below). And, last but not least, visual information has to be present in order to be useful anyhow. In the flight environment, especially that of military aviators, bad weather, darkness, or deceptive conditions may refrain the aviator from adequate visual information. Due to these limitations of the visual system, it is by no means trivial that vision is sufficient to determine a correct sense of spatial orientation.

Circular vection: If we are looking at a moving environment rotating about an earth vertical axis while sitting still, within several seconds we will experience a self rotation, instead of object rotation. This phenomenon is called circular vection. This sense of motion can be achieved by any visual stimulus, as long as changes in contrast are present. No interpretable structures are required, and a random dotted pattern suffices. This means that optic flow, characterised by velocity (here angular velocity) is the determinant of vection. If this sense of self motion is next combined with the deficient sense of self rotation during true self motion when rotating about an earth vertical axis in the dark at constant velocity, these two signals will just add to a veridical sense of self motion. This is illustrated in Fig. 13

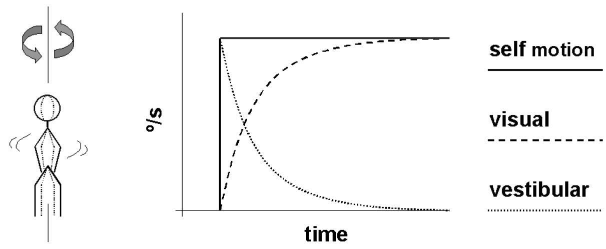

Fig. 13. Circular vection. When rotated about an earth vertical axis, visual motion will result in a slowly increasing sense of self motion, while true body motion will result in a slowly decreasing sense of self motion. The addition of both results in a true sense of self motion.

Linear vection: Something similar holds for linear vection, and this is most often exemplified by the train that is leaving the platform next to ours, inducing a strong sense of self motion in the opposite direction. Because this process is not counteracted by filtering of motion sensor signals as is the case with angular motion, linear vection is much faster than circular vection. Because we do not "see" acceleration, linear vection should be characterised in terms of velocity, and linear motion as sensed by the vestibular system (i.e. linear acceleration) should accordingly be integrated over time before it can interact with the visual velocity perception. At first order approximation we assume a linear weighted addition (c.f. Howard, 1997) of vestibular and visual velocity signals to take place to determine the final linear velocity perception. Vision will generally be dominant in this process (e.g. the train illusion).

Attitude perception: Things get more complicated when describing the visual-vestibular interactions with respect to attitude perception. Then, there are (at least) three factors of interest. First vestibular cues are at steak, as described in the previous section. Second, visual cues can be separated in polarity and frame information. Trees and houses generally point upward, while horizontal and vertical structures aid in determining horizontality and verticality. Lastly, there is also a sense of verticality determined by our own longitudinal body axis. This effect is most evident in weightlessness, when subjects can still indicate their sense of verticality, which, generally aligns with their longitudinal body axis. This contribution is called the idiotropic vector (Mittelstaedt, 1983). These contributions are sketched in Fig. 14, and they are also assumed to interact by means of a linear weighted addition.

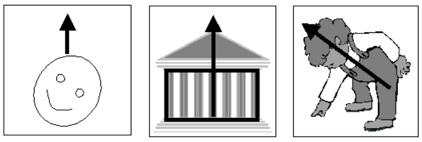

Fig. 14. Three components attributing to attitude perception: vestibular, visual and idiotropic cues. Vestibular perception can be described by a model like that of Fig. 12 Visual information is composed of polarity and frame information. The idiotropic vector is defined as the contribution of the own longitudinal body axis.

A visual-vestibular spatial orientation model

Putting these assumptions together, we come up with a model as sketched in Fig 15. According to this model, spatial orientation is thus characterised by at least four variables, in this case four vectors, with three (Cartesian) components each. These variables are linear acceleration, linear velocity, angular velocity, and our sense of attitude means of the estimate of the gravitational vector. Because linear acceleration is closely linked to force by Newton's second law (**F** = *m***a**), the perception of acceleration may also be closely related to force perception. The estimation of the gravitational vector is also called the subjective vertical (SV). Due to the different interactions involved, the four variables may all behave differently, and are therefore (partly) independent. When characterising spatial orientation this way (i.e. by means of four vectors), it will also be evident that spatial orientation is a complex matter, which interpretation is further complicated by our limited intuitive sense to form a notion of (mainly angular) motions and attitude in three-dimensional space.

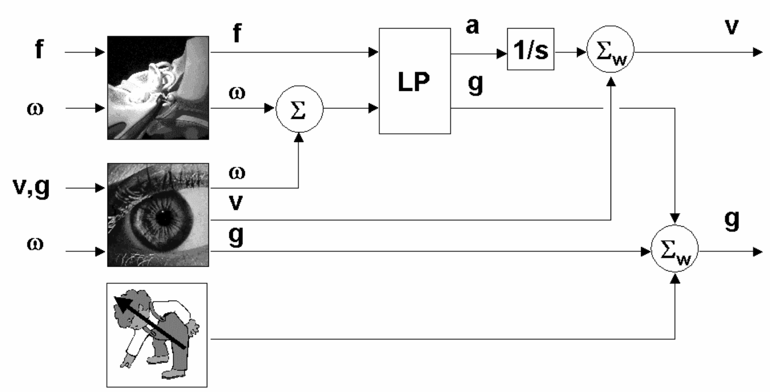

Fig. 15. Visual-vestibular interactions. The vestibular system takes into account the specific force and angular velocity (**f** and **ω**), while the visual system determines linear velocity, attitude, and angular velocity (**f, g** and **ω**). Vestibular and visual velocity signals are assumed to add linearly. The separation of the specific force into an inertial and a gravitational component conform Fig. 12 is represented by the LP-block. Visual velocity and time-integrated vestibular acceleration are also added linearly, however with a dominance of visual information. Vestibular and visual attitude signals are weighted linearly, and combined with the idiotropic vector.

To exemplify this complexity, and yet clarify the use of this model in a relatively simple way, we will consider motion and attitude perception during a takeoff. There are two different ways of simulating a takeoff. One is by means of a Stewart platform, the other uses a centrifuge. The latter is of especial relevance to military aviation.

Two examples

Stewart platform: When only mimicking moderate forward accelerations like that of a typical takeoff of a civil aircraft, a Stewart platform can be used. A takeoff experiment by Groen et al. (2001), using the Stewart platform of the National Aerospace Laboratory in Amsterdam, the Netherlands (See Figs. 16 and 17), is of special relevance here. Their motions are well defined, and they asked (six) experienced aviators for motion and attitude judgements that comply very well with the presently defined model outputs. We will here use a motion profile that was judged to be good, as well as one that was judged to be bad, both intended to mimic a stepwise varied linear acceleration to a level of 0.35g. In addition we will calculate what would have been the outcome given an idealised real takeoff, as well as one with a fixed base simulator. Note that in all cases with vision, the visual stimulus only moved horizontally conform the forward linear acceleration.

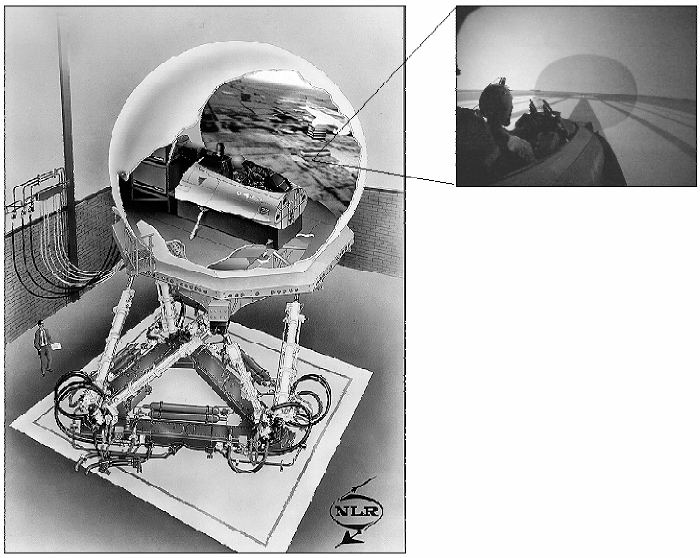

Fig. 16. The Dutch National Simulator Facility, a Stewart platform, as used by Groen et al. (2001) for their take-off experiments.

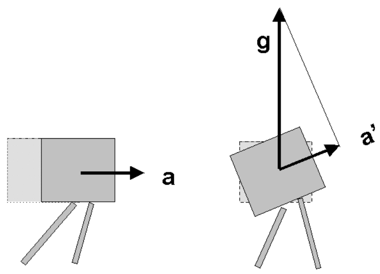

Fig. 17. A linear forward acceleration can be induced by surge as well as by tilt, using the projection of the gravitational acceleration onto the subject’s x-axis. However, due to the limited stroke of a Stewart platform, linear acceleration by surge can only be of a short duration. A tilt, on the other hand, can only be realised slowly in order to remain unnoticed (i.e. by the SCC). The typical acceleration profile of a simulator run therefore shows a dip in the realised profile.

To show the effect of vision on the final results, we also performed all calculations as if no vision had been present. Because the effects of velocity and attitude along the x-axis are largest, we will restrict the data presentation to the projections of the predicted perceived velocity and attitude vectors on the x-axis. Attitude is recalculated in terms of the angle between the x- and z-component of the SV. These data are shown in Fig. 18.

Without going into detail (the interested reader is referred to Bos et al., 2001, 2002), these results can be read as follows. The closer the simulated responses are to the predicted response of a real takeoff the better the run may be anticipated to be. As far as the linear motion perception is concerned (acceleration and velocity), there seems to be not much difference between the predicted responses of the good run and that of the bad run. Here, the effect of vision is most evident, especially in the condition without vision, and this can be understood by the fact that in a real takeoff the vestibular system still experiences a true forward acceleration, while in the simulator only a physical tilt is present. Angular velocity is always below 3°/s, which is assumed to be below the threshold for angular motion perception. When looking at the attitude perceptions, then there is a significant difference between the good and the bad run (most clearly seen in the without vision conditions), the bad run typically showing a greater discrepancy with respect top the perception of a real takeoff. The perception of attitude may therefore be considered to be a (major) factor determining the subjective judgement on the fidelity of the simulator motions. With a fixed base simulator, of all variables that determine spatial orientation, only linear velocity is at stake, and this will generally be too delicate for a faithful sense of spatial orientation. Hence, it seems justified to conclude that indeed the quality of a simulator motion can objectively be rated by the difference between the predicted perception of the simulated motion with respect to that of a real motion. Moreover, a model like presented here gives the opportunity to explain why a good run is good, and a bad run is worse, and it offers the possibility to optimise motion filters by an objective criterion as mentioned, instead of just an intuitive manipulation of motion filter parameters by an experienced technician.

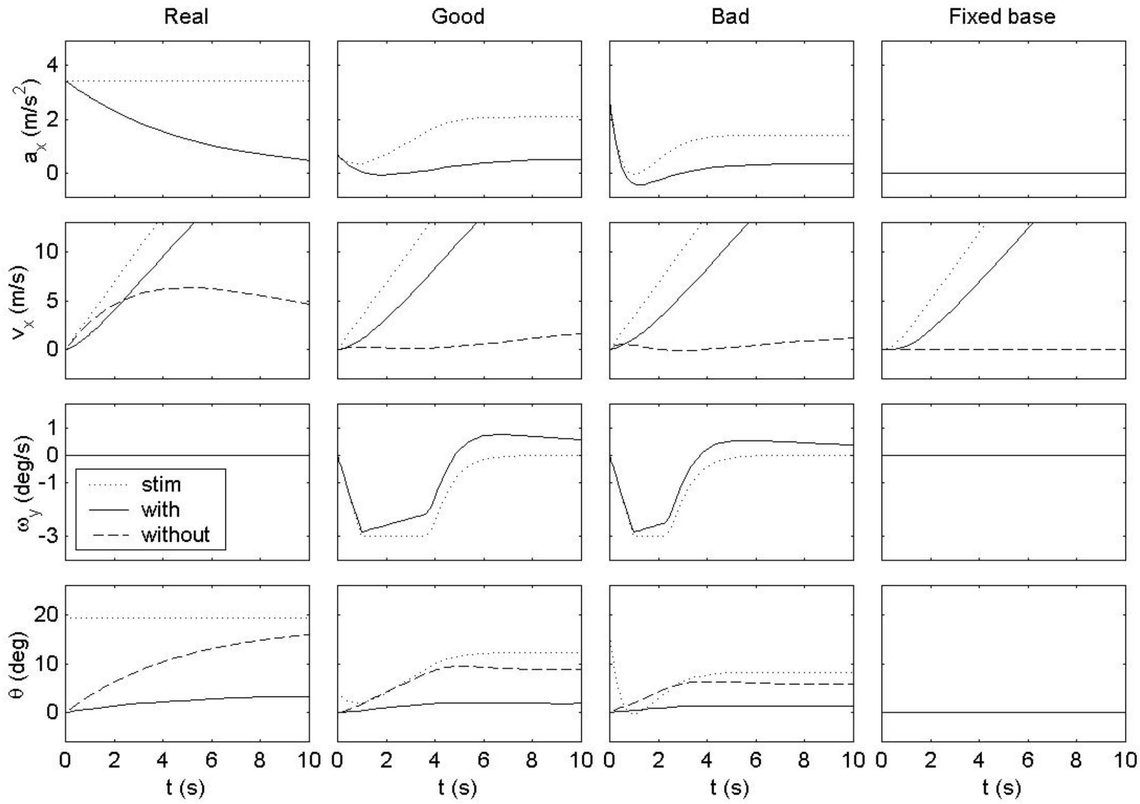

Fig. 18. Model predictions regarding a moderate takeoff simulated by means of a Stewart platform. Left: results of a hypothetical real takeoff. Second left: results of a simulator run judged to be good. Second right: results of a simulator run judged to be bad. Right: results of a simulation with a fixed base simulator, i.e. only visual flow is present. Shown are the predicted perceptions of acceleration (a_x and stimulus acceleration with dotted lines), linear velocity (v_x), angular velocity (ω_y; note that pitch is the only true rotation involved), and tilt (θ). Results with vision are shown by solid lines, without vision by dashed lines.

Centrifuge: A Stewart platform is insufficient when simulating a takeoff with a higher sustained acceleration (i.e. >1g), and this is especially relevant in military aviation. A number of controlled flights into the sea right after nightly catapult launches from aircraft carriers during WW-II and the Korean War can be ascribed to the fact that aviators compensated for the apparent pitch up induced by the high forward linear acceleration (Buley & Spelina, 1970). It is also assumed that every year today a number of controlled flights into terrain can be attributed to this phenomenon. Because long lasting high G-loads can be induced by a centrifuge, this type of stimulation has been used to simulate a catapult launch from an aircraft carrier (e.g. Cohen et al., 1973). When the somatogravic effect (see introduction) is elicited by a centrifuge, however, there is concomitant rotation, definitely supra-threshold, and this rotation does have a large impact on the somatogravic effect (Bos & Bles, 2001). The effect of concomitant angular motion induced by a centrifuge on motion perception is most clearly demonstrated by means of a long lasting linear acceleration as will be considered here. We programmed a hypothetical centrifuge arm length of 3m for these predictions, resulting in a centripetal acceleration of 3g (i.e. $\omega \approx 180°/s$). We here also assume a visual stimulus to be present that is only moving in a forward direction according this centripetal acceleration. The model parameters are kept equal to those for simulating the Stewart platform conditions. Fig. 19 then shows the results, analogous to those of Fig. 18. Because the only angular motion involved here is about the *z*-axis, this will also be the only angular velocity component shown here.

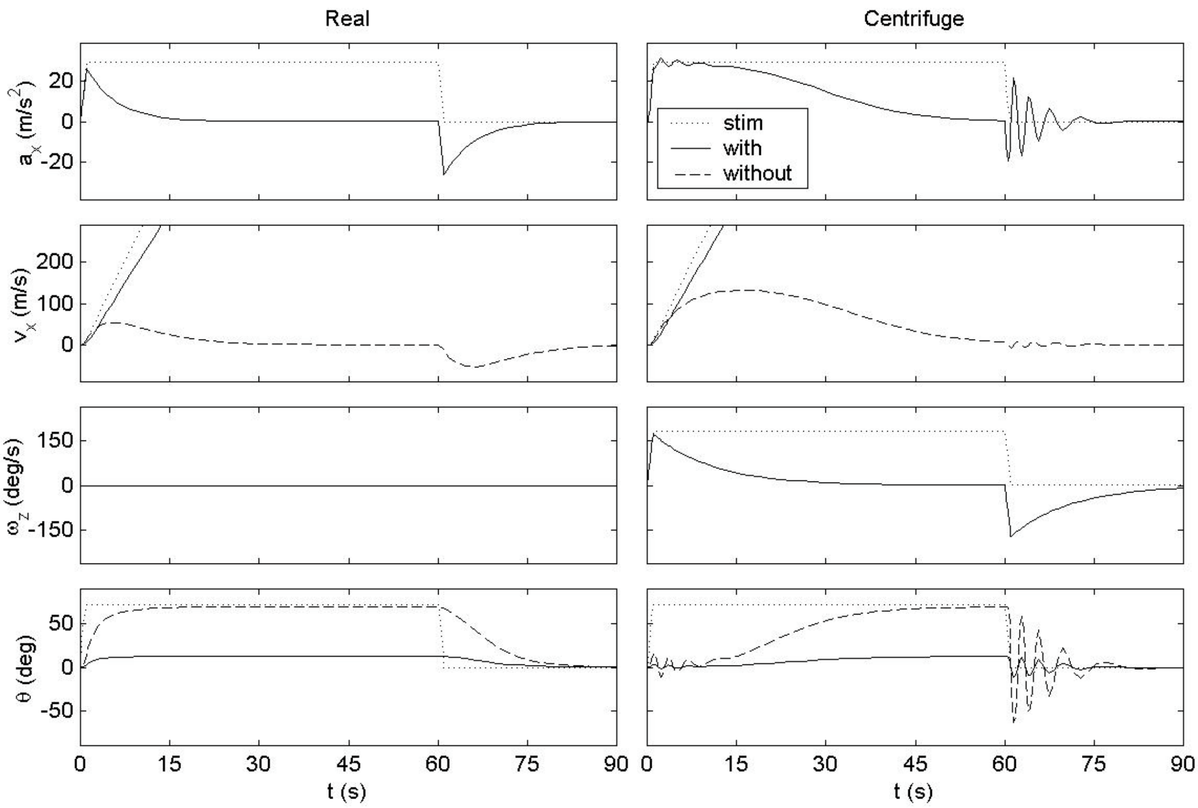

Fig. 19. Model predictions regarding a high-G takeoff. Left: results of a hypothetical real takeoff. Right: results of a centrifuge run. Shown are the predicted perceptions of acceleration (a_x and stimulus acceleration with dotted lines), linear velocity (v_x), angular velocity (ω_z; note that yaw is the only true rotation involved), and tilt (θ). Results with vision are shown by solid lines, without vision by dashed lines.

Most differences concerning motion perception are analogous to the results discussed concerning the Stewart platform takeoff. As opposed to the Stewart platform, however, the perception of linear velocity is larger in the centrifuge as compared to that in a real takeoff when vision is absent. This is due to the concomitant angular motion. Angular velocity is one of the main problems in simulating a high G-load takeoff anyhow. Here, the perceived angular velocity is over 180°/s, which is far above the perception threshold of 3°/s. The angular motion perception is therefore extremely disorienting, and this fact can not be set aside. The most interesting parameter of spatial orientation here concerns the perception of attitude, or the SV. Qualitatively, the model does predict the perception of tilt as it has been observed (see Fig. 6). Note that the curve shown in Fig. 6 represents an average, and the oscillations after centrifuge deceleration have probably been canceled resulting in a large asymmetry. The model also predicts this asymmetry. However, we know now that the perception of tilt is much different in the real situation as compared to a simulated condition. After some initial oscillations (which are no model simulation artifacts), the tilt increases much slower as compared to the tilt due to a linear acceleration without concomitant angular motion. We have previously shown the explicit dependency on angular motion (Bos & Bles, 2001). The most dramatic effect, however, and we have observed this in practice (Bos & Bles, 2001), appears at centrifugation offset. Due to the high-pass characteristics of the SCC, there is a strong rotation sensation after motion cessation, and this signal rotates the subjective vertical (as mathematically described by equation 2). The projection of the SV onto the *x*-axis therefore results in the oscillation as observed. Because acceleration perception is the opposite of tilt (see Fig. 7), acceleration perception will also oscillate in this case. Hence, also by this example, many peculiarities of spatial (dis)orientation can now be understood better, and predicted accordingly. For further details, the reader is again referred to the paper by Bos et al. (2002).

DISCUSSION

We here presented a model including visual-vestibular interactions describing the basic properties of the human spatial orientation system. It hence also explains and describes spatial *dis*orientation. Though not elaborated in detail here, and confined to visual and vestibular cues, the model seems successful in predicting motion and attitude perceptions. We did elaborate the model using a takeoff manoeuvre in real, when simulated by means of a Stewart platform, and by means of a centrifuge. We anticipate that the model, possibly after some further elaboration and optimisation, will also adequately explain and predict the perceptions due to other manoeuvres typical for military aviation, including those of super agile aircraft that have not yet been explored yet.

One extension of the model is likely that by an internal model. In the simple servo model of Fig. 1, sensory deficiencies and CNS delays will directly deteriorate the system's performance. To overcome these problems, it is nowadays believed that the central nervous system uses a so called internal model of the body dynamics, that, when fed with a copy of the motor commands (the efference copy), may give a prediction of body motion that is more accurate than that estimated by our sensory system (Bos & Bles, 2002). If this internal model next includes a copy of the sensory dynamics as well, the difference between true sensory and internal model afferents may be used in addition for adaptation purposes. Optimally this difference should, of course, be zero. We have previously shown that this difference, or conflict, when modelled properly, correlates well with motion sickness (Bos & Bles, 1998, 2002; Bles et al., 2000). Another extension concerns the addition of somatosensory cues, also referred to as "the seat of the pants". If, for example, acceleration perception is linked with force perception as stated earlier, than we will need the interaction with somatosensory cues to command the oscillating perception of acceleration after the centrifuge deceleration in Fig. 19.

Irrespective these possible and likely required extensions of the here presented model, it can be stated by the present knowledge as condensed in Figs. 12 and 15, and the elaboration thereof, that the indistinguishability between accelerations due to motion (i.e. inertial accelerations), and those due to gravity, is the basis of our inability to adequately estimate our sense of motion in all conditions. Hence, *the equivalence principle can be considered to be the main cause of spatial disorientation*. Normally, i.e. under self propelled motion, the solution our CNS applies to disentangle these accelerations does work well. It is, however, only under unnatural conditions, such as sustained hyper G-loads, that anomalies come forth. These problems are next further enhanced by an insufficiency of our angular rate sensors, the semicircular canals. Also for these sensors it holds that under natural conditions they function near perfection, and it again is only under unnatural conditions, such as a sustained constant angular velocity, that they fail.

When vision is present, the visual information normally dominates vestibular cues. However, as demonstrated by the takeoff experiment by Groen et al. (2001) and the succeeding model predictions of motion and attitude perception, visual dominance is not complete, and vestibular cues will always (at least in case of a functioning vestibular system) make their influence felt. Moreover, especially in military flight, the aviator may be deprived from external visual cues due to darkness, bad weather, or hooded conditions, or he may even falsely interpret visual cues (like in autokinesis, false horizon, and lean on the sun illusions). Vestibular cues are the primary factor in determining one's spatial orientation then. Most, if, by definition, not all, SD-mishaps just concern such poor conditions. We will have to reckon that both the visual and a vestibular systems have a limited range of (near) perfection, and the high performance flight environment is definitely out of that range.

ACKNOWLEDGEMENTS

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The Peculiarities of Spatial Orientation of Person in Conditions of G-Influences

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SUMMARY

Six test subjects were subjected to lateral (+$\mathbf{G_y}$) and longitudinal-lateral (+$\mathbf{G_z}$/+$\mathbf{G_y}$) accelerations in a centrifuge with a rotation radius of 6.55 m. During rotation, test subjects were instructed to indicate the position of subjective visual vertical.

Results of this study demonstrated that during exposure to +$\mathbf{G_y}$ and +$\mathbf{G_z}$/+$\mathbf{G_y}$ accelerations, the direction of the indicated subjective vertical approached the direction of the resultant acceleration vector when the lateral component increased. This observed effect decreases with an increase of the longitudinal component of the acceleration. It was suggested that exposure to (i.e. "pulling") high lateral acceleration (up to 2-3 G_y) in highly maneuverable aircraft can hinder spatial orientation of a pilot due to this persistent illusory spatial position as reported above.

Our analysis showed that the process of spatial orientation under the conditions of G-load influence becomes more difficult and it is depending on the compromise between visual and vestibular-proprioceptive inputs. On account of this finding, it may be proposed that under conditions of G-load influence, pilots that rely primarily on visual perception may be exposed to higher risk of spatial disorientation.

INTRODUCTION

Presently, investigators pay ever-growing attention to the methods of correction of perceptual illusions of spatial attitude, limited to the influence of linear accelerations (G-loads), where the resulting gravitational-inertial vector deviates from the longitudinal body (z) axis only. The motivation of this investigation is driven by the possibility of increased pilot spatial disorientation in superagile aircraft such as the Su-30. During superagile flight, the pilot is exposed to lateral G_y and transverse G_x , in addition to the longitudinal G_z-forces.

The inadequacy of the vestibular-proprioceptive apparatus [4] under altered gravitoinertial environments causes the appearance of a wide spectrum of spatial disorientation illusions of different character and expressions (for example, illusion of banking, diving, pitching-up, inverted position etc). These illusions exert aversive effects on the pilot's reliability, as they are prone to exert instinctive reaction to these erroneous cues. In addition it is very difficult to correct for illusions of vestibular origin (for example,

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illusion of contra-rotating) or visual illusions [5]. These illusions, classified as somatogravic and oculogravic illusions, may essentially degrade the pilot's spatial orientation process when flying with the new generation thrust-vectored aircraft.

METHODS

General: The general method for this series of experiments was to measure the subject's perceived orientation while he was at steady state G level. Details regarding the equipment as well as the motivation and method for each phase of the experiment are as follows. Six subjects were exposed to lateral ($+\mathbf{G}_y$) and longitudinal-lateral ($+\mathbf{G}_z/+\mathbf{G}_y$) accelerations, in a 6.55-meter in radius man-rated centrifuge located at the SSRTI MM RF MD, Moscow. The G was imposed by the rotation of centrifuge and "auto-vectoring" of the gondola such that the resultant G vector acted along the lateral or longitudinal-lateral directions with respect to the seated subject inside the gondola. Test subjects were positioned in a seat similar to that in the MIG 29 equipped with two lateral control sticks and with the back inclined at 30° from vertical. The subject was restrained with a five-point harness, and provided G protection with a standard anti G-suit. Subjects also wore a standard issue flight helmet and oxygen mask.

Subjects: Six male, aged 19-28 years of age, employed at the SSRTI MM RF MD volunteered as subjects for this study. The aim and procedures of the experiments were explained, and they were informed that they would have sensations of their spatial co-ordinates during the experiment. They were free to withdraw from the study at any time without reduction in remuneration. Each subject gave general consent and signed the specified documents at each session of the experiment. The protocol was authorized by the Director General of the SSRTI MM. None of the subjects reported any medical problems and all presented with normal vestibular functions. All subjects were assigned to both Experiment 1 and Experiment 2.

Magnitude estimation of rolling illusion evoked by lateral ($+\mathbf{G}_y$) *and longitudinal-lateral* ($+\mathbf{G}_z/+\mathbf{G}_y$) *accelerations:* We used the methods of subjective visual vertical (SVV) and subjective psychometric vertical (SPV) to estimate the effects of the acceleration and the change of the centrifuge gondola position in the static condition.

The equipment used in measuring the Magnitude of Rolling Illusion (MRI) by SVV/SPV is as follows. In order to ensure the safety of the subject during the experiment, SVV method was used [1, 8]. A cross-shaped contour in a head-up display projected to infinity (horizontal component is 10 cm; vertical component is 5 cm) at a distance of 50 cm in front of the subject was mounted in the gondola cockpit. Standard lighting was provided for all conditions. The changes of the contour attitude depend on the subject's strength exerted on the control sticks laterally.

The directions of the contour rotation coincide with the direction of the control-stick force (force to right - contour rotation is clockwise; force to the left - contour rotation is counterclockwise). Contour control-lability from the control-stick force coincided with the following conditions:

$$dP/d_{\omega} = 0{,}362\ kGs/degree.\ s^{-1};\ \ P_{max.} = 31{,}1\ kGs;\ \omega_{max.} = 1{,}5\ degree.\ s^{-1},$$ where:

P - control-stick force, ω - contour rotation angular velocity.

Initially, contour under all experimental conditions was given in the position when its vertical component coincided with the cockpit vertical axis, and the subject's task was to direct it in the position of the subjective visual vertical. At the moment of ascertainment, the subject noted by pressing the button on the control stick and during the next 10-second graphical registration of illusory banking values relative to the initial situation was recorded for off-line data analysis.

A number of control experiments were conducted. Before each G-load influence the subject performed an analogous task during cockpit right banking under static conditions (γ = 15, 30, 45, 60, 75, 90^0) with the velocity of banking at $5^0 sec^{-1}$. Cockpit banking value was randomized for each subject to avoid learning effect.

Method of SPV was used in the experiments where SVV method cannot be employed (for example, when the position of subjects' hands rested on their knees or when the cockpit darkens). With this aim, after each experimental influence the subject noted their subjective position of the vertical line according to a psychometric scale using a vertical semicircle, on which the subject mentally putting himself into the noted point of count (vertical line), pointed value of vertical line on semicircle. The value was measured in degrees relatively to the initial value (coinciding with longitudinal axis of body). The significance of the SPV method was checked under static conditions and G-load influence with simultaneous use of SPV and SPV methods (the latter was the referent method).

In order to provide a standardized analysis of the results, the interpretation of G_Y, G_X, G_Z influencing were compared to the longitudinal, transverse and lateral ($G^0{}_z$, $G^0{}_x$, $G^0{}_y$) load components of the anatomical position of the otoliths. In addition the interpretation is also based on the spatial position of the head (i.e. the angle of inclination, bending, rotation).

Training: Prior to each experiment, the standard G-profiles was given to each subject twice at intervals of more than 1 day. The subjects were required to score the MRI from the second trial on, before they were informed that the stimuli were identical.

Experiment 1

The aim of this experiment was to study the magnitude of roll illusion (MRI) in human spatial orientation under lateral and longitudinal-lateral acceleration influence. The subject was exposed to static conditions and was exposed to the standard G-profiles twice to estimate the MRI by SVV method. The main G-influence profiles were **$+G_y$** = 0,5; 1,0: 2,0; 3,0 and 3,5 units; and after a 5 min rest, **$+G_z$/$+G_y$** = 1,9/1,2; 2,4/2,0, 3,0/2,9 units. In addition, the studies were performed under a static roll of the gondola of 15, 30, 45, 60, 75 and 90°. The duration of the G level last about 30 second. The MRI testing was performed after 12 second. The 12-second stabilization period allowed the dynamics of the semicircular canals to dampen out as their contribution to attitude perception was not a part of this research. Each subject participated in 2 experimental sessions. The combination of the parameters and G-profiles of the test was different in each session, and the order was randomly arranged. The experimental sessions were held at intervals of more than 1 day.

Experiment 2

The aim of this experiment was to study the interaction of visual and vestibular-proprioceptive sensory systems to human spatial orientation with respect to G-lateral and longitudinal-lateral G influence. In order to stimulate tactile-proprioceptive and visual afferent information the investigation was conducted in the following experimental conditions: **A** — binocular vision, hands on the arm-rests of seat, **B** — monocular vision, hands on the arm-rests of seat, **C** — binocular vision, hands on the knees, **D** — eyes are closed, hands on the knees. The main G-influence parameters were **$+G_y$** = 1,0 and 2,0 units; **$+G_z$/$+G_y$** = 3,0/2,9 units after a 5-min rest. In addition the studies were performed under a static roll of the gondola at — 15, 45 and 75°. In condition A SVV and SPV methods were used, but in conditions **B**, **C** and **D** - only SPV method was used. Each subject participated in 1 experimental session. The combination of the G-profiles of the test was different in each session, and the order was randomly arranged. The experimental sessions were held at intervals of more than 1 d.

Statistical Analysis: To examine the stability of the MRI measurements, we examined whether MRI changed during the course of the trials. A regression line was fitted to the relationship between the MRI values and the order of trials by the method of least squares, and the significance of the gradient of the estimated regression line was tested by F-test (analysis of variance: ANOVA).

RESULTS AND DISCUSSION.

The results of the SVV measured at **$+G_y$** and **$+G_z$/$+G_y$** loads influence **(Experiment 1)** are illustrated in **Fig.1.** The results show that in conditions of **$+G_y$** and **$+G_z$/$+G_y$** load influence, subject indicated subjective vertical, together with the increase of lateral component, that coincides with the direction of resulting force vector. This effect decreases with the increase of longitudinal component of G loads. According to the given mechanism the creation of subjective vertical is accompanied by the appearance of expressed and firm rolling illusion, which is at an average 17.2 ± 4.5^0; 33.4 ± 7.1^0; 56.4 ± 12.1^0 during the influence corresponding to $+\mathbf{G_y}$ = 0.5;1.0 and 2.0 unit that could affect pilot spatial orientation in flight.

From this information it is apparent that the rolling illusion at lateral loads influence increased with the increase of lateral tangential component in otolith plane **($\mathbf{G^0y}$)**, and it confirms the main mechanism of otolithic irritation (the influence of tangential force removal). The character of this dependency in general coincides with logarithmic (Weber-Fechner) or power (Stevens) laws «stimulus-sensation» for wide range of subjective reactions [6, 7]. At the same time, at $\mathbf{G^0_y}$ = 0,5; 1,0; 2,0 units SVV meanings were lower than resulting vector deviation ($\mathbf{G^0y}$) at the average for 81; 47; 15 % accordingly, but at $+\mathbf{G^0_y}$ = 3,0 and 3,5 units they practically coincided.

As illustrated in **Fig. 1., $+\mathbf{G_z}/+\mathbf{G_y}$** loads influence were also accompanied by rolling illusion increase according to $\mathbf{G^0_y}$ component increase, nevertheless, significantly lower than the analogous interpretation of $\mathbf{G^0_y}$ in conditions of lateral loads influence. Even in $\mathbf{G^0_y}$ lateral component of more than 2.5 units, SVV indications were vector deviated (not shown in Fig 1) for 30% and 17% accordingly.

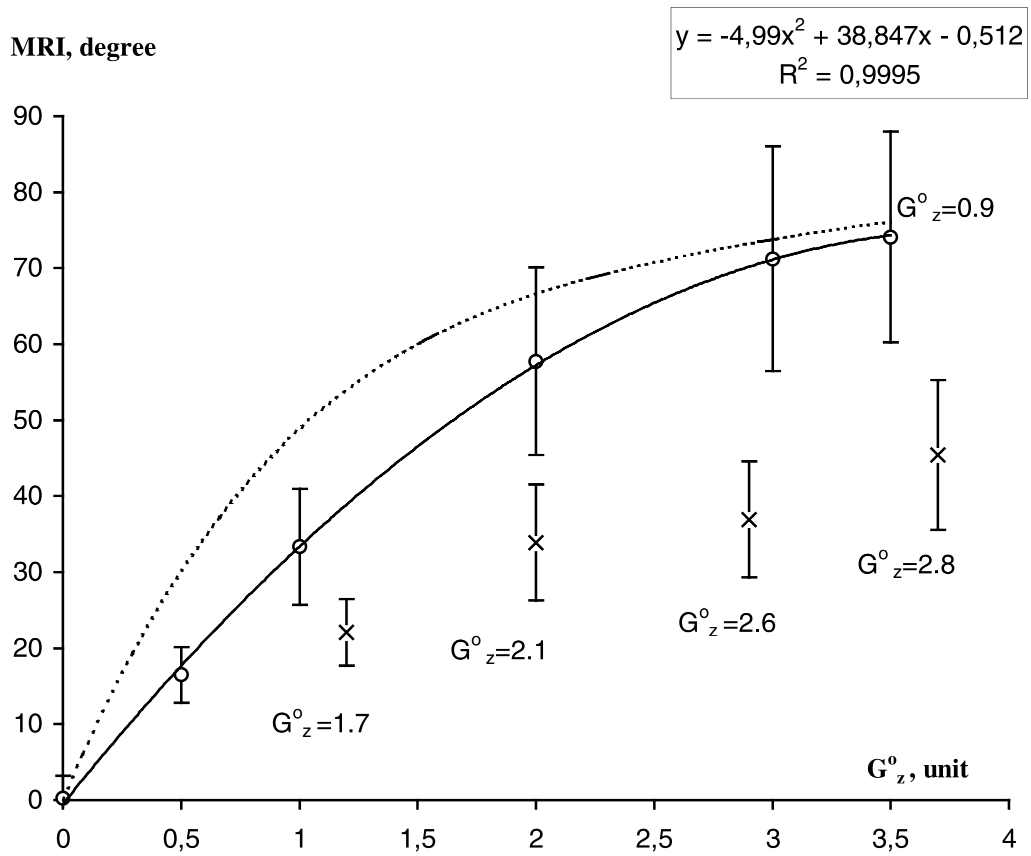

Fig. 1. The meaning of rolling illusions (entire line) and deviations of resulting gravitoinertial vector (dotted line) depending on load lateral component value at the influence of lateral (o) and combinated lateral-longitudinal (x) loads.
(M ± S.E.; n = 12). The notes are in the text.

The results from **Experiment 2** show that, in general, the difficult compromise between stimuli under conditions of sensory conflict is an individually dependant characteristic, which could be termed as "preferable modality of perception" [2].

Under static roll of the gondola, the differences observed between a subjective roll value using the SPV-method under various experimental conditions were absent. Under G-exposure (**see Fig. 2.**) the degree of MRI on the basis of SPV-indices and subjective values changed according to experimental conditions with marked individual features. In 4 subjects with eyes opened, the transfer of hands from armrests to knee was accompanied by a MRI-decrease, especially under $+\mathbf{G_y}$ = 2,0 units. With eyes closed, degree of MRI did not change. In two subjects the opposite situation was observed. The transfer of hands from armrests to knees under the eyes opened condition was not accompanied by a change in the roll illusion, but with the eyes closed, a significant increase of roll illusion was observed, especially under $+\mathbf{G_y}$ = 2,0 units and $+\mathbf{G_z}/+\mathbf{G_y}$ = 3,0/2,9 units.

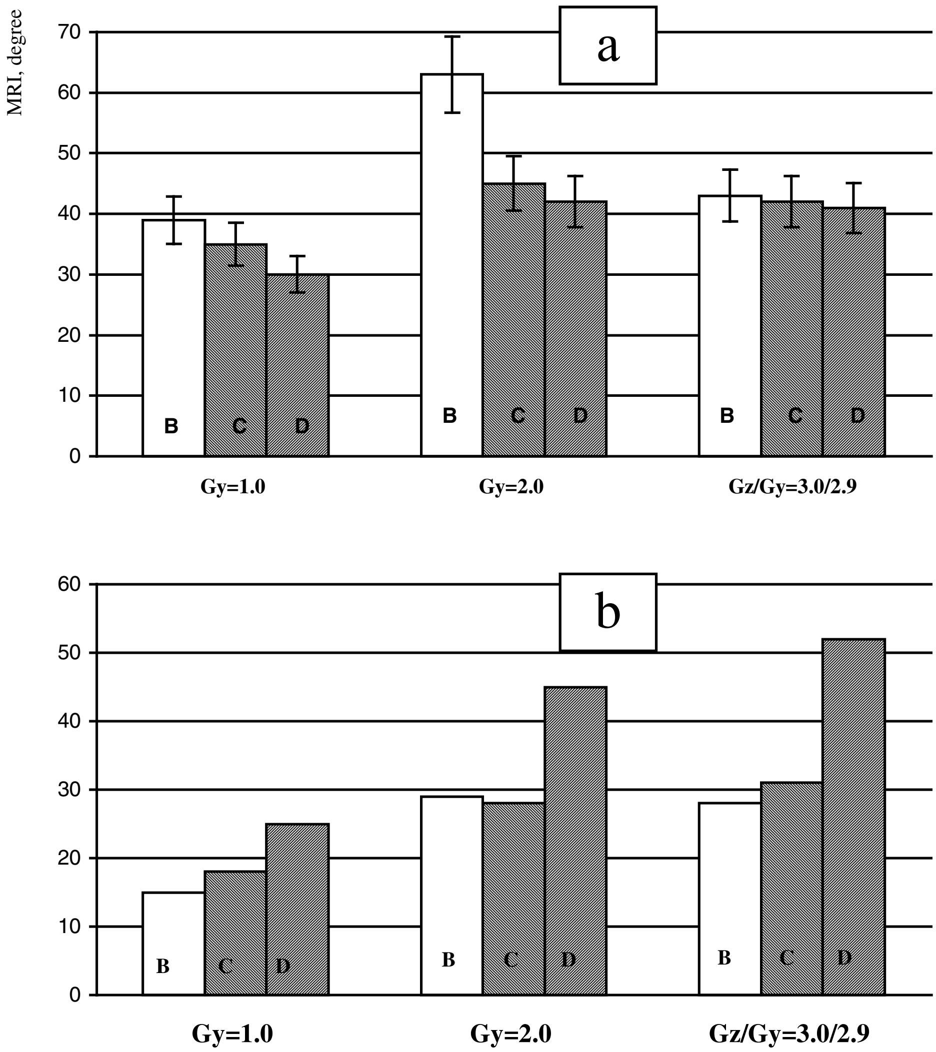

Fig. 2. Marked rolling illusion (on SPV method) at $+G_y$ and $+G_z/+G_y$ loads influence depending on experiment conditions.
Note: «a» (M±m; n=4), «b» (M; n=2), the rest notes are in the text.

The increase of MRI was accompanied by subjective reports after the trials. Subjects described their sensations as "sense of endless roll", "constant rotation to the right", "impossible to determine the spatial attitude", "expectation of impact on the floor". Specified groups of subjects varied on the MRI-manifestation under G-exposure in the control experimental conditions (A). In the first group the MRI-manifestation has practically corresponded with the magnitude of deviation of resulting gravitoinertial vector and was on the average of 2-3 times higher, than in the second group.

Our results can be interpreted in terms of the availability of individual preference of perception modality. Realization of complex compromise between stimuli in the conditions of sensory conflict is an individual characteristic, which is termed as “preferable modality of perception” [2, 3]. Some subjects prefer vestibular-proprioceptive information, to the detriment of visual one, but others — visual information, to the detriment of vestibular-proprioceptive. Under **$\pm G_y$** and **$+G_z/G_y$**-exposures, the probability of spatial orientation disturbance could be expected by persons with “preferable visual modality of perception”, in comparison with the persons having “preferable vestibular-proprioceptive modality of perception”.

Our analysis shows that the process of spatial orientation under conditions of G-load influence depends on individual peculiarities of a compromise between visual and vestibular-proprioceptive information. The ultimate definition of subjective spatial co-ordinates is different among persons with vestibular-proprioception and those with visual modality of perception. In the first case the illusions are expressed, but changed little in the presence and character of visual reference-points, and in the second case - the illusions are expressed a little with the presence of adequate visual reference-points and increased greatly in their absence. Taking the above into account, it is proposed that in conditions of G-load influence because of the lability of subjective spatial co-ordinates, pilots with visual modality of perception may have higher risk of spatial disorientation.

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The Role of "Extra-Vestibular" Inputs in Maintaining Spatial Orientation in Military Vehicles

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Summary
An individual's sense of spatial orientation is commonly attributed to be derived from visual, vestibular, and proprioceptive inputs. Spatial disorientation is often ascribed to arise from a conflict between one or all of these three systems. However, relying on this well studied view of spatial perception has not totally explained motion intolerance and spatial disorientation. It is likely that more than these three systems are involved in spatial orientation. This paper examines how cues obtained from posture, respiration, and blood flow contribute to spatial orientation. Disordered regulation of any of these factors can be identified in land based tests and allows us to study pre-disposing factors to motion sickness. In addition, examining these factors in motion environments allows us to study the mechanisms involved in motion intolerance. Postural studies were obtained in a cohort of individuals experiencing motion sickness in a variety of military environments. A definite pattern of altered postural control on land was demonstrated in over seventy percent of these individuals. The predictive value of this test and refinement of the test for increased accuracy as a pre-screening method are examined in this report. A second cohort of individuals was examined while underway in a United States Navy ship. Respiratory and postural measurements were performed on 3 motion sick and three non-motion sick individuals within 24 hours of going to sea as well as 48 hours after the first measurement. Initial postural and respiratory adaptations were compared to ship motion and the strategies of individuals without motion sickness were compared to the strategies of the motion sick individuals. Adaptive patterns were examined in each group and found to be complete within 48 hours. The implications of these findings are examined in developing strategies to deal with spatial disorientation in a number of military settings. Technology is examined that might help us to better test individuals for adaptive strategies and train them so that spatial disorientation is not an issue in a planned operational event.

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Introduction

Traditional teaching holds that balance control requires an integration of visual information (the eyes), vestibular information (the inner ears), and proprioceptive information (the hips and the ankles). These inputs are hypothesized to be integrated at the level of the brainstem for reflex control and this integrated message is interpreted at a higher cortical level. The traditional view also focuses on reflex loops such as the vestibular-ocular reflex that coordinates eye and head motion and the vestibular-spinal reflex that coordinates head on spinal cord motion. While the traditional explanation of coordinated balance explains how humans generate adaptive reflex responses to postural challenges and some aspects of orientation perception under static conditions, it does not offer a coherent explanation for phenomena such as motion sickness, mal de debarquement and motion adaptation disorders. [1,2]

The sensory conflict theory of motion sickness states that motion sickness arises when one or several inputs from the body's sensory systems are in conflict (disagree) with inputs from other sensory systems and do not match previous neural patterns.[3] With only the traditional balance system this theory does not explain why drivers of cars rarely experience motion sickness while the same individual as a passenger in the car (even in the front seat) will experience motion sickness on the exact same drive.[4] Certainly, the sensory conflicts in the traditional balance system are no difference whether you are sitting on the left or right side of the car. In addition, the traditional balance system does not explain why individuals experience simulator sickness in full motion simulators, which are designed to mimic operational flying scenarios, whereas the same individuals do not experience motion sickness when the simulator does not move as much. Certainly, the sensory conflict is greater in the lower motion simulator. Because we could not explain human spatial orientation in a motion environment based on the traditional balance system, our group began to examine "extra-vestibular" inputs into the balance system. We believe that, especially in a motion environment, a set of influence primarily generated from the trunk may be very important in humans maintaining spatial orientation. For the purposes of this discussion, the term "extra-vestibular inputs" refers to inputs from parts of the body that are not "traditionally" considered to influence balance. We will present three pieces of evidence that suggests that bodies under the influence of motion rely on inputs outside of the traditional vestibular-visual-proprioceptive system to sense position and to maintain posture and spatial orientation.

Postural Stability and Motion Sickness

At the Department of Defense Spatial Orientation Center (DSOC) we have had an ongoing trial examining a group of patients with significant chronic intractable motion sickness (CIMS). The individuals in this study must have several episodes of severe motion sickness during an operational military assignment (usually aboard ship), but demonstrate no balance disorder or ear pathology when not in a motion environment. Examining some of the vestibular testing results in this group of patients provides us one piece of evidence that supports "extra-vestibular" inputs into the balance system.

Materials and Methods

Individuals presenting to DSOC with chronic intractable motion sickness that had presented during several operational assignments were admitted into the study as were a set of control subjects selected to mirror the sex and age distribution of our patients. All of the individuals in the study underwent an extensive history and physical examination for balance function. Balance function tests included Rotational chair testing (Micromedical Inc., Chatham, Illinois) and Computerized Dynamic Posturography Testing (CDP) (Neurocom Inc., Portland OR). Rotational chair testing consisted of the following: 1) Sinusoidal harmonic acceleration .02, .08, .32 and .64 Hz at a maximum velocity of 80 degrees/sec^2, 2) Visual fixation suppression (VFX) testing at .04 Hz SHA at 60 degrees/sec^2 velocity and vestibular-visual interaction testing

(VVOR) at .04 Hz and 60 degrees/sec^2 velocity, 3) Computerized rotation chair velocity-step testing at 100 degrees/ sec^2 for clock wise rotation (CWR), clockwise stop (CWS), counter clockwise rotation (CCWR) and counter clockwise stop (CCWS) , and 4) Computerized rotation chair oculomotor function tests. CDP testing included the following tests: 1) The six Sensory Organization Subtests, 2) The Motor Control (Linear Translations) Subtest, and 3) The Adaptation Tests (Toes-up and toes-down).

Results

The motion sick group of patients consisted of 18 active duty individuals (13 males/ 5 females) The age range was 19-36 years of age with a mean age of 27 years of age. This group was compared to a control group of 18 active duty individuals (13 males/5 females) with an age range of 23-38 years of age and a mean age of 30 years of age. There was no significant difference between the demographic factors in the two groups. On functional vestibular evaluation all members of both groups reported no disequilibrium or dizziness on land. However, CDP testing was normal in all of the members of the control group, whereas 72% of the motion sick group of patients had abnormal CDR results particularly in conditions 5 and/or conditions 6.

Discussion

Our results indicate that a high percentage of individuals with motion sickness demonstrate postural control abnormalities. This is in agreement with the findings of other groups. [5,6] We believe that these postural control abnormalities are fundamental to stability in motion and are at least partially responsible for motion sickness. This argument is supported by findings from two subsets of these individuals who responded to vestibular rehabilitation therapy. One group of patients was composed of individuals who had abnormalities in the vestibulo-ocular reflex (VOR) (as measured on rotational chair testing) and who normalized their VOR function with therapy. Despite the improvements in testing, these individuals continued to experience motion sickness. The second subset of patients was those who demonstrated abnormalities on CDP testing and whose abnormalities improved with therapy. These individuals were cured of motion sickness.

Findings in our motion sickness group of patients support the fact that posture affects spatial orientation and stability particularly during motion and that those who lack postural control will have difficulty with spatial orientation in a motion environment. This difficulty with spatial orientation is expressed as motion sickness and/or anxiety.

Anatomical Findings

The realization that there are extravestibular sensors for sensing gravitoinertial acceleration is base on the recognition that all tissues in the body have mass. The implication of this truism is that gravitoinertial acceleration will impact directly on pulmonary function,[7] movements of the abdominal viscera within the peritoneal cavity [8,9](sensed by traction on mesenteries, contact with parietal surface of peritoneum and stretch due to pressure on diaphragm),[10, 11] regional blood distribution (including 'orthostatic responses'), intraocular pressure,[12] and intracranial pressure.[13] The reader is referred to a review chapter by Balaban and Yates (in press) for a detailed discussion of each of these potential mechanisms.[4] A brief overview of biomechanical bases for these effects has been included below.

The mammalian torso is divided into an abdominal/pelvic cavity and a thoracic cavity, separated by a musculotendinous septum, the diaphragm. These cavities are surrounded by striated muscles that move the trunk (e.g., intercostal muscles, abdominal muscles, sternocleidomastoideus and scaleni) and muscles of the pectoral girdle that have the capability to change the configuration of the torso and volume of the internal cavities. The thoracic viscera are contained in a median compartment, the mediastinum (e.g., heart and esophagus), and paired lateral pleural compartments.

The abdominal contents can be divided into two component systems that are affected directly by gravitoinertial acceleration, [14] organs tethered (directly or indirectly) to the diaphragm and organs that are connected loosely to the posterior abdominal wall. [15] As verified by dissection in primates, the thoracic surface of the diaphragm is tethered by the attachment of the pericardial sac both to the central tendon of the diaphragm and the muscular part of the left dome of the diaphragm. The abdominal surface is attached firmly to the liver by the coronary ligament, the right and left triangular ligaments and the appendix fibrosa hepatis (an extension of the left triangular ligament). As a result, the mass of the liver may be viewed as a load on the diaphragm, ligaments of the liver and pericardial attachments that are sensitive to the direction of gravitoinertial acceleration. On-going studies are investigating the distribution of mechanoreceptor-like nerve endings in the regions of attachment between the diaphragm, pericardium and liver.

The abdominal viscera, on the other hand, are covered by a visceral peritoneum, which forms both a dorsal mesentery that suspends the viscera loosely from the posterior abdominal wall and a small ventral mesentery that attaches stomach and proximal duodenum to the anterior abdominal wall. This loosely tethered gastrointestinal tract can be viewed as a fluid-filled balloon that deforms when subjected to a linear acceleration. Thus, it produces a variable gravitational load on the diaphragm during attainment of various postures (supine, lateral decubitus, prone or inverted), such that the earth-down aspect of the diaphragm is loaded differentially.[14,16] These factors appear to be determinants of gravity-dependent gradients in transpulmonary pressure,[15] respiratory movements during locomotion[9] and respiratory function during water immersion[14] and microgravity conditions.[17] It seems clear that these effects of gravitoinertial acceleration may improve local visceral and somatic motor control in the face of gravitoinertial challenges during imposed and self-generated movement.

Changes in the orientation of the orthostatic column are another potential source of information regarding changes of the orientation of the long axis of the body relative to gravitoinertial acceleration. Regional changes in blood pressure and blood volume are detected by arterial baroreceptors, atrial and ventricular pressure receptors, epicardial receptors, pulmonary and renal baroreceptors and venous stretch receptors,[10] many of which respond to both steady-state blood pressure and to the rate of change (derivative) of blood pressure.[10,18]. These receptors comprise the afferent limb for orthostatic responses, which maintain mean blood pressure in the face of an orthostatic challenge. However, in a broader sense, orthostatic reflexes (feedback control of mean blood pressure) and the phenomenon of 'baroreflex resetting' preserve the sensitivity of baroreceptor afferents to rapid changes in body orientation.[19] In the same way that gamma motoneurons match the operating range of stretch receptors in muscle spindles to the length of extrafusal muscle fibers, one role of baroreflex mechanisms can be conceived as ‘rezeroing’ the blood distribution so that the orthostatic column can respond to rapid changes in body orientation relative to gravity. Thus, baroreceptors can be said to function as accessory graviceptors.

Additional Findings

There are two additional findings that support an “extra-vestibular” input into spatial orientation. We have observed that on board ships individuals may entrain their breathing to the motion of the ship. In preliminary studies performed in our lab individuals on a ship were examined within 24 hours of departure of the ship. Those individuals who were experiencing motion intolerance displayed shallow, rapid breathing. At the 72-hour mark these individuals were re-examined and, in those who were no longer experiencing motion intolerance, their breathing was in phase with the ships roll frequency. Those individuals that continued to have motion intolerance continued to breath out of phase with the ships roll frequency. The influence of respiratory control on motion sensitivity cannot be explained by traditional balance theory.

Finally, we have demonstrated that a significant portion of individuals with clinical vestibular disorders respond to physical conditioning (exercise) alone with resolution of symptoms. Other than a small amount of strengthening of the legs, this exercise does not impact elements of the "traditional balance system". However, this cardiovascular conditioning does alter blood flow and cardiovascular performance. We feel that this cardiovascular improvement effects a portion of the bodies "extra vestibular" inputs and allows for the improvement in balance function noted in these patients.

An "Extra-vestibular" Input into Balance and Spatial Orientation

Based on the preliminary findings and to explain some of the ambiguities that occur when only the traditional vestibular theory is applied to some situations in motion environments, our group has proposed that the body uses a set of "extra-vestibular" inputs in spatial orientation. We believe that the body utilizes information gained from respiration, body posture, and the distribution of blood flow to help determine at least the position of the trunk in space. It is possible that a portion of the body's 'gravitoinertial framework map' is based on the experience of receptors associated with the hollow viscera of the abdomen and to the diaphragm and present inside blood vessels. Since childhood, the body learns that certain positional changes or certain postures exhibit a different set of influences on these extra-vestibular receptors. The gravitoinertial framework map may be based in part on the influences of extrinsic linear acceleration (including gravity) on movements of the small and large bowel, on dynamic movements of the ligament-tethered complex of the diaphragm, liver and stomach and on the distribution of blood in the vasculature. During quiet respiration in a static gravitointertial frame, the actions of gravity are unambiguous. However, in a moving frame, such as oscillations of a ship near respiratory frequency, the sum of the extrinsic motion and the self-generated respiratory movements may produce ambiguous information from abdominal and thoracic receptors if the motions are not in an appropriate phase relationship. Motion sickness, then, would simply a referred gastrointestinal distress from these ambiguous (conflict) situations.[4]

This modified sensory conflict framework may be applied to other situations in the same way as traditional sensory conflict theory. For example, the pilot "pulling G's" for the first time experiences a whole set of influences on the "extra-vestibular system" that may be in conflict with the traditional vestibular system. Over time a new extra-vestibular flying map is formed for this situation and as the pilot flies more the amount of spatial disorientation decreases. Once that pilot is placed in a flight simulator where the extra-vestibular signals are not the same as those in flight, a mismatch is created between the perceived vestibular and extra-vestibular information and this mismatch results in simulator sickness. Similarly, on board ships or in other operational environments, motion sickness or spatial disorientation can result when "extra-vestibular" information confounds or contradicts vestibular, visual and proprioceptive information. However, this conflict may be resolved by simple behavioral adaptations, such as entraining respiration with movement of a ship. This phenomenon may parallel the phenomenon of 'getting one's sea legs', whereby the motions of the ship become a baseline, stable framework for locomotion. Those who lack the appropriate adaptive learning capabilities (or who choose poor 'adaptive' strategies) will therefore not resolve the conflict and will suffer from motion sickness just as our patients have displayed.

The significance and exact mechanism whereby the "extra-vestibular" apparatus effect balance function demands further study. A research project is underway in our labs to more fully characterize the function of "extra-vestibular" inputs in determining spatial orientation. At the current time our theory is based on preliminary data and observed phenomenon, it must be backed up by solid science.

Implication of "Extra-Vestibular" Input into Spatial Orientation
The presence of "extra-vestibular" inputs into the balance system has significant implications especially to a military environment. The presence of these inputs presents a new set of targets for strategies to reduce motion intolerance and perhaps even increase (produce "super normal") spatial perception. The possible significance of "extra-vestibular" inputs into balance suggests that certain ergonomic design changes in military vehicles could minimize "neural map" mismatch or that training in an actual replica of an operational device might begin the process of formation of a new "extra-vestibular" map which would not be in conflict with the traditional vestibular system when the vehicle was truly being utilized. In addition, the presence of "extra-vestibular inputs" further supports the work of CAPT Rupert, as it is possible that the "balance suit" at least partially relies on "extra-vestibular" stimulation to "inform" the body of its spatial orientation.

Conclusion

Traditional teaching holds that balance function is based on three sets of inputs visual, vestibular, and proprioceptive. Work by our group, a consortium composed of members of the United States Military and investigators from the University of Pittsburgh, has begun to demonstrate that additional inputs may play a role in spatial orientation. These "extra-vestibular" inputs come from respiration, posture, and blood flow distribution and may play an important role in spatial orientation especially in motion environments. Our group is actively involved in basic research to determine the presence and significance of these "extra-vestibular" inputs. The presence of these inputs might provide a unique target for the treatment of vestibular disorders, the prevention of motion intolerance, and, even, the augmentation of spatial orientation in operational and non-operational settings.

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G-Transition Induced Loss of Orientation and Reduced G Threshold

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SUMMARY

It has been suggested that the psychophysical and physiological responses to the interplay of rotation and acceleration stresses may result in spatial disorientation (SD) (18, 4). The purpose of this presentation is to review past and current evidence on the possible relationship between disorientation and acceleration stress. Accident scenarios and a number of in-flight observations will be presented together with some theoretical postulates on the mechanisms involved. Our investigation suggests that execution of a series of rapid roll manoeuvres prior to or following G transition may lead to loss of attitude awareness. This loss of attitude awareness can be attributed to perceptual confusion during roll maneuvers and the normal response of the vestibular apparatus to the rotary accelerative force acting on the semicircular canals. In addition, G threshold can also be significantly reduced immediately after prolonged rotation. This phenomenon is supported by past and current scientific evidence that the vestibular system exerts an influence on cardiovascular control. The next generation of high agility aircraft has enhanced maneuverability, which will expose pilots to a combination of translational and extraordinary angular accelerations. An understanding of the interaction between SD and acceleration stress is crucial to establish future research initiatives that will lead to appropriate countermeasures.

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INTRODUCTION

In the past 50 years, considerable progress has been made in understanding the mechanism of spatial orientation. Research on visual and vestibular inputs to orientation led to the understanding of some of the visual and vestibular causes of spatial disorientation (SD) in flight. Concerns over reactions to accelerations of high performance fighter aircraft motivated studies of the conditions that differ considerably from the range of motions that occur commonly in everyday life. For example, the perceptual responses generated by the otolith organs under sustained, higher than normal G forces were quantified. However, ground based and in-flight research on attitude perception is generally studied under the controlled change in direction and magnitude of resultant force vectors relative to the body and head. Some of the flight profiles used in these in-flight studies were dissected into single manoeuvres that typically occur in rapid sequence in flight. The two common elements that pilots are exposed to during fighter manoeuvres are rapid transition of G levels and roll maneuvers that are not possible to duplicate during ground based research. It has been reported that flying high performance fighter aircraft during offensive and defensive maneuvers regularly imposes a frequently changing force environment with multiple high G excursions (10). The frequency distributions of Gz levels during air combat maneuver in the F-18 shows that only a small proportion of each sortie was spent at moderate-to-high +Gz levels, the percentage of the sortie above +3Gz is about 7-9% (20).

Pilots frequently perform transition between high G and high roll rate in air combat. Flight path changes depend on “reorienting the lift vector”. That is, the pilot maneuvers against his opponent by rapidly changing his flight path. This is accomplished by tilting or rolling the aircraft’s lift vector so as to change the plane of flight. The roll rate of most aircraft decreases markedly at high Gs and at higher angles of attack. When the pilot wishes to rapidly change the direction of flight, he/she will reduce acceleration or angle of attack, roll quickly to a new attitude and rapidly re-apply acceleration to “position the nose” of the aircraft against the opponent. This is true in both offensive maneuvering, such as scissors maneuvers, and in defensive maneuvers such as the “guns jink”. In other words, modern fighters are exposed to substantial linear and angular acceleration throughout the air combat manoeuvre. It has been suggested that the psychophysical and physiological responses to interplay from rotation and acceleration stress could result in SD. This paper attempts to review evidence that may support the possible relationship between disorientation and acceleration stress and begins with the description of two F-20 accidents that occurred under almost identical conditions.

F-20 ACCIDENTS INVOLVING HIGH G AND HIGH ROLL RATES

In 1984 and 1985, while practicing for air-shows, two fatal mishaps involving the F-20 occurred under very similar circumstances. The visual environments of the two accidents were also very similar with an indistinct horizon where the sky and ground lacked distinct color contrasts. The air show routine, the estimated G and the airspeed across time are shown in Table 1. Both accidents occurred near the end of the air show routine where, after a series of maneuvers involving G transitions, a 9 G pull up to the top of an “Immelman” turn, was followed by aileron rolls, and then the procedure called for a lowering of the landing gear for the final turn back to runway. Both mishaps terminated with the pilots flying the aircraft into an incorrect attitude from which they could not recover. The first one made the 9 G pull up and aileron roll and put the landing gear down but the aircraft was still inverted as the gear came down. The aircraft remained upside down for several seconds and there was an attempt to push the nose up from inverted, however the pilot could not recover and crashed. In the second accident, the F-20 made the 9 G pull up which was to be followed by a 1½ aileron roll to upright. Instead of rolling to upright, the aircraft stopped at an inverted attitude. After close scrutiny of the video of the accident, it appears that the aircraft over-banked slightly and corrected to exactly inverted when the pilot began to pull. The speed and the nose were too low to recover.

Another test pilot who had flown the identical flight profile experienced visual disruption. At about the same time frame, after the 9 G pull followed by the aileron roll, when the roll maneuver was terminated, he lost sight of the instrument panel, canopy bow and cockpit sidewalls. He reported seeing colors and saw faint brown and blue hues. However he reported that he was fully awake, alert and aware of his predicament. When his full vision returned, he was aware that he was in fact upright and the blue hue was the sky and the brown was the desert. The effects of G transition and rapid roll maneuver on the cardiovascular and spatial orientation system likely played a role in these mishaps.

EFFECTS OF G-TRANSITION

Almost 50 years ago, during an in-flight study, von Beckh reported that the effects of exposure from hypogravity to hypergravity included reduced G tolerance, G-induced Loss of Consciousness (G-LOC) at lower G values and at shorter G duration. In addition, there was a reduced efficiency in physiologic recovery mechanisms and subjects experienced higher strain (2, 3). The effects of the reverse, i.e. hypergravity to hypogravity transitions included pronounced disorientation and extended duration of G-LOC. von Beckh referred to the reduced G-tolerance and greater strain as “a logical consequence of the transition from hypogravity to hypergravity”. It was reported that the transition from hypergravity to hypogravity induced a sensation of flying in an inverted position, although no negative acceleration had been present (2). This is probably one of the early reports of the inversion illusion prior to Lieutenant B.C. Neider’s report of personal inversion while free floating during parabolic flights. Regarding disorientation related to G-transitions, von Beckh speculated that it was due to unfamiliar vestibular cues. In practice, a pilot, pulling sharply out of a dive, may experience gray-out or blackout. In order to halt the developing loss of vision, he or she may push the stick forward so that the aircraft enters a parabola. In this event the pilot may experience weightlessness, and his/her loss of sight and spatial orientation caused by the changing G’s may even be prolonged.

EFFECTS OF RAPID ROLL MANEUVER ON CARDIOVASCULAR FUNCTION

When a seated subject is rotated at constant speed about the corneoretinal axis, as defined by Hixson, Niven, and Correia (11), or more commonly known as the roll axis, blood flow along the longitudinal body axis is subjected to two force components. One is the centripetal force, $\omega^2 r$, where ω is the angular velocity and r is the radius of rotation. The other is gravity, which varies sinusoidally between +1Gz when upright and –1Gz when inverted. If the axis of rotation is below the pilot (as in high performance fighters) greater negative Gz can be experienced by the pilots. The component of the Earth’s gravitational field must be added to, or subtracted from the above according to the aircraft’s position in roll. Acceleration changes would quickly build up as a result of changes in the angle of pitch of the aircraft. However, it is the overall effect of these factors, which appears significant. Pulling +Gz, following a point-roll or unloaded barrel roll involving –Gz, can result in reduced G-tolerance as described in the preceding Section.

It has also been observed that the G threshold of some pilots is significantly reduced immediately after recovery from a prolonged rotation (14). Subjects were more liable to blackout at lower G levels than in situations where exposure to increased acceleration was not preceded by rotation. Vestibular stimulation has been shown to cause a significant decrease in blood pressure and reduction in heart rate by Spiegel (24). More recently, it was shown that high angular acceleration of the head about the yaw axis reduces the baroreflex responsiveness by 30%, suggesting that high angular rotation inhibits vagally mediated baroreflex control of heart rate and impairs orthostatically induced tachycardia (8). Recent animal studies provide convincing evidence suggesting that the vestibular system is involved in compensating for posture-related changes in blood pressure. Decerebrate cats with intact vestibular pathways (26, 27) demonstrated an increase in sympathetic nervous system output during pitch rotation, but not during roll rotation.

In humans, there is some evidence that orthostatic hypotension induced by head-down to head-up tilt in pitch orientation is more effectively compensated than head tilt in roll (5). The greater sensitivity to pitch is partially attributed to the fact that whole body rotation in roll is rarely executed.

INTERFERENCE WITH VISION DURING PROLONGED ROLL ROTATION

Modern fighter aircraft are capable of rapid rates of roll, and it has been reported that for a rapid rolling manoeuvre (≥ 200 °/s) the maximum number of continuous revolutions compatible with maintenance of a clear sense of orientation is roughly 3 to 5 depending upon type and rates of roll of the aircraft (14). During a roll maneuver the pilot is looking forward. The associated nystagmus due to vestibular and optokinetic stimuli will be about the nasooccipital axis, termed torsional nystagmus. Relatively little information is known about the dynamics of torsional eye movements induced by high-speed roll rotation in flight. It has been suggested that the rate of rotation might have been too great for compensatory eye movements to follow fixation upon the outside world or the instrumental panel when subjected to roll rates as described. Melvill Jones (15) obtained cine recordings of pitch, roll and yaw eye movements of pilots during eight-turn spins in flight. The results suggested that compensatory eye movements during the maneuver failed to stabilize the retinal image, with the greatest discrepancies in the roll plane. A laboratory study (17) upheld the conclusion that in the yaw plane optokinetic influence predominated over the vestibular-ocular reflex, whilst in the roll plane the reverse relation held and the vestibular influence was dominant. However, the optokinetic influence in the roll plane cannot be completely neglected.

More recent laboratory studies have all indicated that sinusoidal rotation of the head about the roll axis through about ± 10-15° produces little retinal slip near the fovea and so head rotation about the roll axis needs not be fully counteracted by eye movements (7, 19, 23). As in other frontal eyed animals, human torsional nystagmus should not affect visual acuity. The finding that torsional gain is lower than horizontal or vertical is partially attributed to the fact that human VOR has little experience with purely torsional head rotations, because our head rotation axes for eye-head gaze shifts normally lie within about 15° of the frontal plane.

EFFECTS OF ROLL ROTATION ON ATTITUDE PERCEPTION

Perceptually, while rolling, a pilot can become confused over the visual indicators of horizontal (12). One manifestation of visual confusion is that pilots misread the artificial horizon (22). They could become confused about whether the horizon or the aircraft symbol in the attitude indicator is locked to the gravitational vertical. Also, they can become confused about whether the entire display (and the aircraft) is erect or inverted. In flight, the resultant gravitoinertial force is aligned with the pilot’s z (spinal) axis, which could add to the confusion. During a level roll manoeuvre, the pilot retains his orientation in the aircraft cockpit but not with respect to gravity or the outside visual scene. The direction of the gravitoinertial force rotates around the pilot's head while the interior of the aircraft rotates at the same velocity with respect to the direction of gravity. If external vision is ambiguous, the only visual information available to the pilot for self-orientation is the inside of the cockpit and the visible parts of the pilot's body. If recovery is delayed, impression of the outside world could become blurred and the rate of rotation may appear to speed up. Upon recovery, when rotation is suddenly brought to a halt, an after sensation of rotation is experienced in the opposite direction and this is associated with an apparent rotation of the horizon (oculogyral illusion) and deflection of the horizon indicator. It has been reported by pilots that in practice they could neither fixate upon their instruments nor upon the visual field at the higher rates of rotation (13). Only a blurred impression of alternating dark and light was obtained.

Another effect that may lead to loss of attitude awareness during roll maneuvers stems from the short time constant in roll. The effective time constant of post-rotational decay is considerably shorter in roll which implies that a greater rate of development of error in the roll axis (16). During a period of steady rotation about any body axis the inputs from the semicircular canals cease. For rotation about a non-vertical axis, inputs from the otolith organs continue. This might have contributed to the post-roll effect – the Gillingham illusion as described by Clark and Graybiel (6) and Ercoline et al (9).

In general, there is a lack of dynamic attitude perception studies due to the difficulty in obtaining reliable information on the dynamics of spatial orientation perception on the ground and especially in the air. A large volume of perceptual data for static conditions such as sustained body tilt and perception of body tilt or tilt of a visual target are available. However, information on the dynamics of attitude perception during altered gravitoinertial environment is sparse. The effects of roll rotation in-flight on torsional nystagmus and post-rotatory judgement of self-orientation and visual orientation to gravity remain to be investigated.

CANAL RESPONSES TO RAPID ROLL ROTATION

During rotation with rapid onset rates, the cupula of the semicircular canals may be maximally deflected before the maximum stimulus is attained. In other words, the magnitude of the angular acceleration experienced is at times greater than the maximum that can be recorded by the semicircular canals. Therefore, the sensation of direction of rotation may be at times either opposite or less than that which was in fact occurring. The misleading sensation that may have been experienced is similar to that usually found when rotation is suddenly brought to a halt – the after sensation of rotation experienced in the opposite direction which is associated with the apparent rotation of the visual field.

VECTOR RELATED VERTIGO

Finally the effects of G transition and rapid rotation have also been noted in the civilian world. Civilian aerobatic pilots routinely experience both hypo- to hypergravity and hyper- to hypogravity transitions in excess of +9 to –3 Gz, as well as roll and yaw rotations at rates ranging from 20 to over 400°/s (associated with rapid onsets and sudden decreases). Over the past 10 years there has been an increasing awareness of a phenomenon of the sudden onset of vertigo, loss of balance, and extreme nausea, known as the “wobblies” among pilots (21). The phenomenon appears to occur predominantly after flight when the pilot deplanes and begin to walk. An F-16 pilot of apparent good health experienced sudden onset of severe near incapacitating vertigo following the completion of a “check-six” (looking back over the shoulder) maneuver over his left shoulder during a +7-8Gz turn (25). Upon landing, physical examination revealed that forward head tilt and rotation produced vertigo with SD predominating. A presumptive diagnosis of benign paroxysmal positional vertigo was made. It has also been documented that the dizziness experienced can be severe when pilots turn their heads, and may persist for 3 weeks or longer (1). Although the symptoms are similar to benign paroxysmal positional vertigo, the apparent etiology is unknown. The syndrome would just as well be explained by a possible mechanism involving the brain stem as it is near the main acceleration axis. In view of the next generation agile aircraft, intensive research is required to delineate this condition. In the interim, the condition is best managed clinically by recognition, and allowing time for spontaneous recovery. The likely persistence of symptoms after landing suggests that assisted exit from the aircraft is prudent and pilots should avoid repeated “insults”.

CONCLUSION

In-flight research on the conceptualization of changing orientations, directions and magnitudes of the angular and linear acceleration vectors relative to the head throughout complex motion profiles representative of aerial combat is necessary. A pilot's G tolerance may be liable to a reduction as a result of maneuvers that will provide strong vestibular stimulation that are routinely undertaken in air combat maneuvers. Further investigation in this area is warranted. Specifically, extreme pitch used in aerial combat and the repeated and very intense roll exposures accompanying them may have significant vestibular and cardiovascular consequences. The interaction of spatial disorientation and acceleration is an important issue since next generation thrust vectored superagile aircraft provide multi-axis maneuver capability. As technology progresses it is also probable that these same problems will be found in underwater maneuvering when using supercavitation principles for motion. An integrated approach to spatial disorientation and acceleration research should be developed in order to recommend the most appropriate countermeasure.

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TABLE 1. F-20 Airshow Routine

Time (min.sec)	Event	Approx Gz	Approx Speed - KCAS
0.00	Release brakes	1	0
0.15	Left climb 90° turn	1.8	155
0.23	Right aileron roll to right bank	1	200
0.27	Right 270° turn back to runway	3	200-350
0.49	Left knife-edge pass	1	375
0.56	Pull up to full Cuban 8	4	400
1.16	2 right aileron roll over top of Cuban 8	2	250
1.21	Pull up into second leg of Cuban 8	4	375-400
1.26	Right roll on "up" leg of Cuban 8	1	275-300
1.43	Inverted pass	-1	400
1.52	Right roll to upright pull to cloverleaf turn of 90°	7	425
1.56	2 left aileron rolls at top of 90° cloverleaf	1	250
2.03	270° turn back to show-line	3	250-400
2.21	1 aileron roll right, 1.5 aileron roll left to left bank	1	400-425
2.28	Level 360° turn	6	350-450
2.50	Pull up to loop	4-5G	450
3.03	2 left rolls coming over the top of the loop	0.8	250
3.19	Left 80° roll to L270° level turn	4-5G	250-450
3.36	Right Climb pull up for 120° heading change	9	450-230
3.45	1 left aileron roll	1	250-230
3.51	Left 270° turn to final	1	230-155
4.04	Touchdown	1	135

Head Position Control and Target Localization Performance in Changing Gravito-Inertial Field

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Summary

A subject seated in a modern vehicle (i.e., aircraft) and performing motor tasks may be submitted to inertial forces (Coriolis and centrifugal forces). These forces are sources of spatial disorientation, leading to perturbations of sensori-motor behaviour. The coding of the position of the head, which carries visual and vestibular sensors, is of particular interest with regards to this problem. We have investigated the influence of the position of the head on the accuracy of pointing movements towards visual memorized targets performed in a modified gravito-inertial field in 10 subjects seated 70cm off-centre on a platform rotating at 120°/s. Subjects' head was either strongly immobilized in a vertical position (aligned with gravity vector) or completely free to move. Subjects were required to point as accurately as possible flashed visual targets presented in total darkness, before (PRE-rotation), during (PER-rotation) and after rotation of the platform (POST-rotation). Position of the head in the head free condition was recorded with an electromagnetic movement sensor (Polhemus Fastrack), whereas pointing accuracy as well as kinematics of the movements were recorded with an infrared position sensor device (Hamamatsu Motion Monitoring System).

Whatever the position of the head (head free or head restrained), rotation of the platform induced errors in pointing towards flashed visual targets in the direction of the new imposed forces (to the right in our experiment). However, the errors were greater when the subject's head was free to move than when maintained in a vertical position. Results obtained in the head free condition show a strong correlation between the angular position of the head during rotation and the increased errors in pointing movements.

Our data demonstrate that a change in the position of the head during rotation of the platform may have a strong effect on the accuracy of goal-directed behaviours. Reaching at a visual target requires transformation of visual information about target position with respect to the line of sight, into a frame of reference suitable for the planning of hand movement (body-centred reference frame). Our data suggest that coding of the position of the head during centrifugation may be inaccurate, leading to errors in localizing the real position of the presented target relative to the body. Our experiment confirms that modification of the position of the head during centrifugation may be a source of disorientation. It seems that fixation of the head in a given position may reduce the emergence of spatial disorientation. Moreover, recent data obtained in our laboratory suggest that peripheral visual information may help subjects to stabilize their head in a given position and reduce target localization errors.

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Introduction

Under normal terrestrial conditions, the force of earth gravity accelerates object, including us, down toward the surface (center) of the Earth. With experience, the brain establishes relationships between gravity, joint torques, and movements and thus integrate gravitational effect into internal dynamic models (Shadmer and Mussa-Ivaldi, 1994). As a consequence, orientation and sensory motor control mechanisms are normally dynamically tuned to this constant background acceleration level (Lackner and Dizio, 2000). The existence of such a calibration is usually 'perceptually transparent' to us so that we are not aware of the sensory and motor accommodations (motor commands have to continuously include an antigravitational component) that we make in relation to gravity. This calibration allows subjects to perform goal-directed behaviors with considerable accuracy in a variety of conditions (Atkeson and Hollerbach, 1985; Papaxanthis et al. 1998). For instance, Papaxanthis et al. (1998) asked their subjects to perform vertical arm pointing movements in two directions (upwards and downwards). Their results suggested different planning processes, for movements with and against gravity and indicated that gravitational force influences the processes controlling movement execution. However, when gravity is not the only force acting on individuals (for instance a subject seated in a car taking a bend), new inertial forces, that are the Coriolis and centrifugal forces, may represent a potential source of perturbation of goal-directed behaviors (Bourdin et al., 2001; Lackner and Dizio, 1998). In such conditions, subjects have to integrate these new inertial conditions to act. If not the case, goal directed behaviors may become less accurate than usually. For instance, a recent study showed that no complete motor adaptation[1] to the perturbations created by centrifugal and transient Coriolis forces may occur if visual feedback about reaching accuracy is denied (Bourdin et al, 2001). This study confirmed the predominant role of the vision on the ability to adapt to modification of the gravito-inertial field.

However, sources of errors in pointing movements performed in modified background force level remain largely unclear. Several explanations have been proposed in literature, as already mentioned by Bock et al. (1996). Clearly, perceptual as well as motor errors have been proposed to encounter the results, these sources of errors being not mutually exclusive. Perceptual errors include the possible mislocalization of the visually presented targets, as well as the possible altered coding of the limb position provided through proprioception. Motor errors include the direct mechanical effect of the gravitoinertial vector as well as the existence of an inappropriate motor commands to the background force level. These two types of errors were also investigated by Watt (1997) in a study analyzing accuracy of pointing movements towards memorized targets during prolonged microgravity. Watt hypothesized that the errors made when pointing actively at memorized targets during microgravity may be due to (a) a loss of an "internal spatial map", leading to not knowing where the arm was pointed, (b) a loss of an "external spatial map" leading to not knowing where the target was. His main objective was to determine the relative contribution of each of these potential sources of errors. Watt concluded his study in rejecting the hypothesis of a shift of the internal spatial map. According to him, inaccuracy in goal-directed movements towards memorized targets performed in microgravity was mainly due to uncertainty as to target location.

Our study is mainly concerns with the question of the perceptual errors and their consequences on the accuracy of pointing performances in modified background force level. One particular point, neglected in previous experiments performed in modified background force level, is the influence of head position on the accuracy of goal-directed behaviors. Head is the support of visual receptors as well as the vestibular apparatus, suggesting that head status is of particular importance in planification and execution of goal-directed movements performed in a modified background force level. Many experiments, performed in normo-gravity field, have shown that reaching at a visual target requires transformation of visual information about target position with respect to the line of sight, into a frame of reference suitable for the planning of hand movement, i.e. centered on the head, the trunk, the shoulder or the hand (body-centered reference frames) (Jeannerod, 1988; Blouin et al., 1993). The mechanism controlling egocentric visual localization and orientation is determined by inputs from the body-referenced mechanism (Retinal local sign information, extraretinal eye position information, extraretinal head orientation information) and from the visual field. Then, accurate coding of head posture seems an essential prerequisite to accuracy of goal-directed

[1] A remarkable and well-studied ability of the human brain is that of adapting the execution of limb movements to physical changes in operating conditions such as those that naturally occur during exposure to altered mechanical environments (Dizio and Lackner, 1995; Goodbody and Wolpert, 1998; Shadmer and Mussa-Ivaldi, 1994). This process is known as motor adaptation.

movements, in the sense that signals related to head position might be a cue for monitoring target position. According to this hypothesis, Biguer et al. (1984) compared the accuracy of hand pointing movements in a situation where the head was fixed and in a situation where it was free to move. Their results showed that the errors in pointing towards targets were considerably reduced for all targets in the head-free condition, especially for more eccentric targets.

In modified background force level, position of the head is submitted, as well as the other limbs, to new inertial forces, leading to possible changes in its position during a centrifugation protocol. In such dynamical condition, one of the prerequisite for the subjects to be accurate in pointing towards memorized targets is to precisely code the new head position relative to the body. In total darkness, vestibular cues as well neck afferents may play a crucial role in the coding of head position and then in the performance of goal-directed behaviors. The vestibular system includes two types of sensors: the semicircular canals and the otolith organs. The semicircular canals behave as integrating angular accelerometers measuring head angular velocity. The otolith organs provide information about head orientation with respect to the gravitoinertial force vector; under static conditions, this corresponds to head orientation vis a vis gravity. Proprioceptive neck afferents signals also play a major role in determining head position relative to the trunk.

However, accuracy in the proprioceptive coding of limb position (the head could be considered as a limb) has been questioned in gravitoinertial force field (Worringham and Stelmach, 1985). Indeed, these authors have suggested that the proprioceptive coding of limb position was less accurate in hypergravity (or micro-gravity) than in normo-gravity. For instance, under terrestrial conditions, head orientation in relation to the gravitoinertial resultant modulates muscle spindle sensitivity through otolith spinal mechanisms acting on the anti-gravity musculature of the body (Wilson and Melvill Jones, 1979). Moreover, results obtained by Bourdin et al. (2001) tended to show that proprioceptive signals on limb position can not lead to complete motor adaptation to modified background force level, and that vision was necessary for retrieving a high level of accuracy. This suggests that coding of head position during exposition to increased background force level could be less accurate than in normo-gravity condition. This type of sensory distortion may be a source of errors in pointing movements to memorized targets observed in previous experiments performed in modified background force level (Bourdin et al., 2001), because under these conditions the subject's body can serve as the coordinate system in which the movement is planned (Soechting and Flanders, 1989).

The main purpose of this study is to analyze the influence of head position on the accuracy of goal-directed movements performed in modified background force level. In a second level of analysis, we will be able to question the accuracy of head position coding in modified background force level and its relationships with motor performance.

Materials and Methods

Participants

10 right-handed subjects, aged from 18 to 35 (mean age = 23) took part in the experiment. None of the subjects had a history of vestibular abnormalities or other neurological disorders. All participants were unaware of the purpose of the experiment, and gave their informed consent prior to the beginning of the experiment.

Task and apparatus

A schematic representation of the experimental set-up is shown in figure 1. Subjects were comfortably seated on a rotating platform at 70 cm from the right of the axis of rotation. Tests were conducted with the platform either stationary or rotating counter-clockwise around its vertical axis at constant velocity (constant angular velocity of 120°/s). During rotation of the platform, subjects were submitted to a modification of the gravitoinertial vector (modification in amplitude and orientation). The resulting gravitoinertial force (Pythagorean sum of gravitation and centrifugal force) was 1.05g at subject's position. The gravitoinertial vector was inclined at 17.38°. A four-point safety belts was used to prevent body movement relative to the chair during the experiment and particularly during the rotation of the platform.

Seated subjects were facing a pointing table equipped with three red Light Emitting Diodes (LEDs) serving as targets to be pointed to. These three LEDs were positioned on a half circle, 30 cm radius centered on the subject's hand. A radial rather than linear disposition of the LEDs was chosen in order that the subjects could execute nearly the same movement amplitude from the body axis to every target. From the subjects' viewpoint, the targets were at 20° to the left (Left Target), 20° to the right (Right Target) and centered on the sagittal plane of the subject (Central Target). The targets were recovered with Plexiglas to suppress all tactile information on their position.

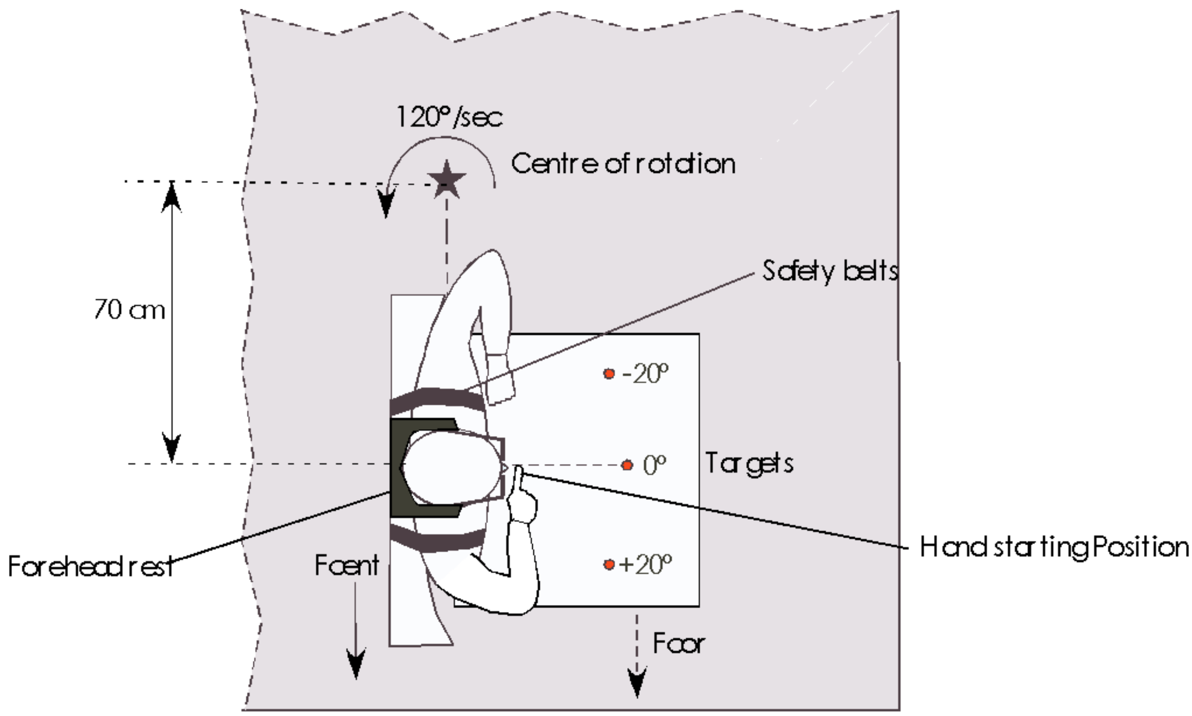

Figure 1. Schematic representation of the experimental set-up used in the experiment. Direction of the centrifugal force (Fcent) and of the Coriolis force (Fcor) during rotation of the platform are represented. Forehead rest was used to prevent any movement of the head during the HR session and safety belts prevented any movement of the trunk during both experimental session*s*.

Procedures

Subjects were instructed to point with their preferred hand towards flashed visual targets (200 msec.), as accurately as possible. No time instruction was given to the subjects to allow maximum accuracy in the pointing task. Each subject participated in two experimental sessions. The first session was performed with the head fixed in a vertical position (vertical axis of the head aligned with the vertical axis determined by the gravity) (Head-Restrained condition, HR), whereas the second session was performed with the subject's head free to move (Head-Unrestrained condition, HU). In the HR condition, the trunk and head axes were kept closely aligned, whereas they were dissociable in the HU condition. In HR condition, the subject's head was stabilized in the natural upright position for looking straight-ahead by means of two rigid posts, covered with hard rubber, which pressed very firmly against the forehead. This forehead rest was designed to suppress the possibility of head movement about the three axis of rotation. At the start of the HR condition, position of the subject's head was regulated so that central target was exactly aligned on the sagittal plane (at the objective straight ahead, body midsagittal), so that the central target coincides with the cyclopean eye.

During HU condition, no instruction was given to the subjects concerning their head position. However, they were recommended no to produce fast movements of the head during rotation to prevent motion sickness.Each experimental session was divided into three blocks of 45 trials (15 trials for each targets), for a total of 135 trials. The three blocks were : (a) pre-rotation (PRE, no rotation of the platform), (b) per-rotation of the platform (PER) and (c) post-rotation (POST, no rotation of the platform). Subjects performed all conditions in a complete darkened room and wore soldered glasses to be sure that no visual information (except the flashed target) was available. Both the onset and the offset of the platform's rotation produced a rotatory nystagmus. To eliminate its undesirable effect, which lasted a few seconds, the pointing movements in PER and POST condition started 1 minute after the end of the acceleration or deceleration phase. Order of the sessions was counterbalanced between subjects so that some subjects performed the HR session in first and the HU session in second and vice-versa. A few days separated each session. An experimental session lasted 1 hour in all.

Position in space of the head during the HU condition was recorded along three axes of rotation using a Fastrak (Polhemus) system. The Fastrack sensor was fixed on a low-weight helmet secured to the subject's head. The Fastrack emitting source was placed 50 cm beside the subject. These data were sampled at 120 Hz. Pointing movements were recorded with an infrared position sensor device at a sampling frequency of 200 Hz (Hamamatsu Motion Monitoring System). The monitoring system consisted of a matrix made of small infrared-emitting diodes positioned on the right index fingertip and an infrared-sensitive camera fixed perpendicularly above the table.

Data analysis

Angular errors (errors in direction) were computed by subtracting the target angle from the angle of the actual movement endpoint. Errors to the right of the target (in the sense of the inertial forces) were given a negative sign, whereas errors to the left (opposite to the direction of the inertial forces) were given a positive sign. Moreover, to overcome systematic errors in the pointing movements, we calculated normalized angular errors by subtracting the mean errors in direction made in PRE for each subject from those made in all conditions (PRE, PER, POST).

We were also interested in the kinematics of the pointing movements performed during the experiment. We analyzed movement time, as well as amplitude and time to peak velocity. Movement onset was defined as the time at which the tangential velocity reached 2.5 cm/s. Similarly, the first point in time that the velocity dropped under 2.5 cm/s was considered as the end of the movement.

Analysis of the head position during the experiment was based on two main angles that were computed as dependent variables. Roll angle was defined as the angle of the longitudinal head axis with the earth vertical, taken positive for right-ear-down rotations and negative for left-ear-down. Yaw angle was defined as the angle of the sagittal head axis with the earth sagittal plane, taken positive for head rotated to the left and negative for head rotated to the right. Pitch angles were not included in the analysis because preliminary analysis showed that rotation of the platform did not induce shift in the head position in pitch.

All the data concerning hand movements were submitted to 2 Head postures (Head Unrestrained and Head Restrained) x 3 Rotations (PRE-rotation, PER-rotation and POST-rotation) x 3 Targets (Right, Central and Left targets) analyses of variance (ANOVA) with repeated measures on all factors. Data on head position in HU condition were submitted to 3 Rotations (PRE-rotation, PER-rotation and POST-rotation) x 3 Targets (Right, Central and Left targets) analyses of variance (ANOVA) with repeated measures on all factors. Post-hoc analyses used the Newman-Keul's test.

Results

Analysis of Pointing movements

Normalized angular errors

Analysis of variance for normalized angular errors revealed a significant main effect of Rotation ($F(2,18)=18{,}98$; $p<.001$), and a significant interaction Head x Rotation ($F(2,18)=6{,}56$; $p<.01$). Our results showed that, whatever head position, normalized angular errors in pointing movements towards memorized targets were directly dependent on the condition of rotation of the platform, that is on the presence of new inertial forces. Indeed, with the platform in rotation, subjects made larger angular errors (4.73°) than when the platform was stationary (respectively, O° and –0.17° for PRE and POST conditions). Subjects pointed to the right of the presented targets during rotation of the platform, that is in the direction of the new inertial forces. This results confirms previous results obtained by Bourdin et al. (2001) on the influence of centrifugal and Coriolis forces on the accuracy of pointing movements made in complete darkness.

As illustrated in figure 2, the accuracy of pointing movements during rotation (PER-rotation) of the platform was significantly influenced by head position, whereas no significant effect of head position was found in PRE and POST-rotation. When subjects' head was free (HU condition) during rotation of the platform, subjects made greater angular errors (5.65° to the right of the targets) than when their head was fixed in a vertical position aligned with the trunk (HR condition, 3.82°) (p<.001).

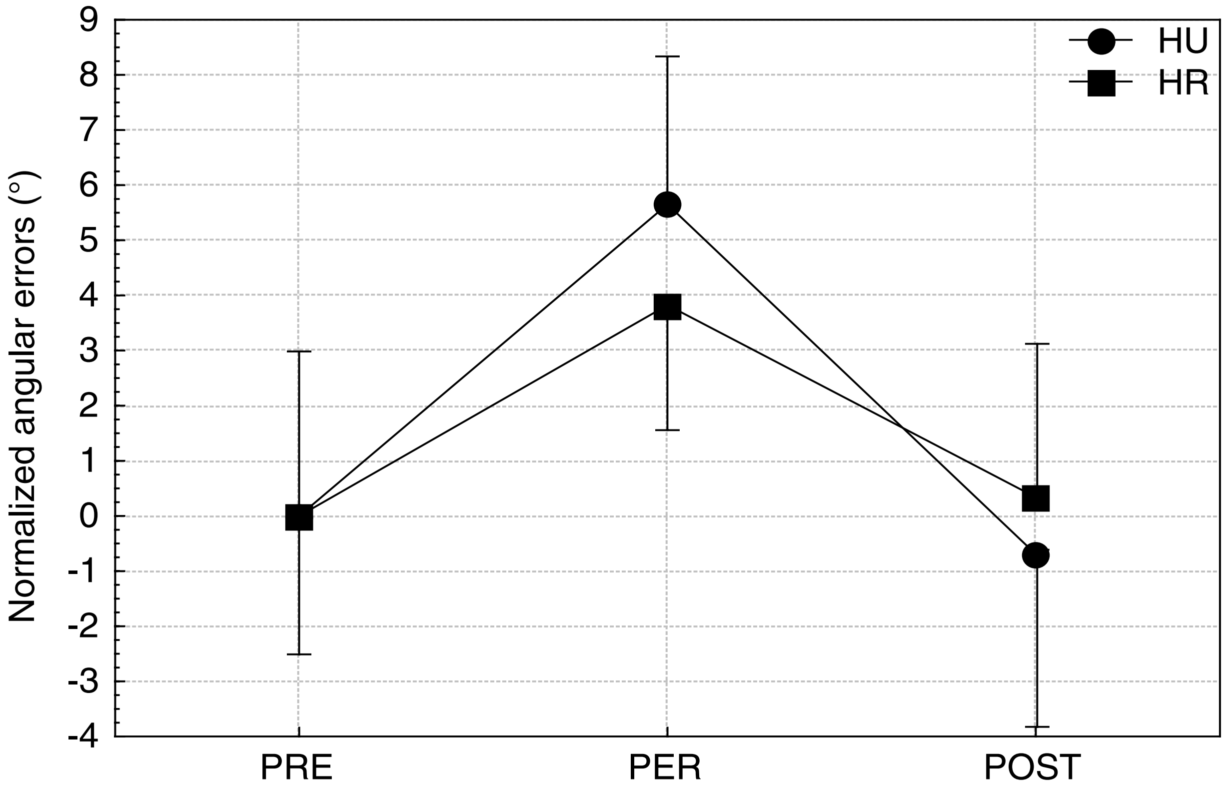

Figure 2. Mean and standard deviations of the normalized angular errors in function of the condition of Rotation and of Head Position. HU represents the session performed with the head free, whereas HR represents the session performed with the head fixed and kept aligned with the trunk during the experiment.

Movement time

The ANOVA revealed that rotation of the platform as well as position of the head did not significantly influence movement time when pointing to memorized targets. Whatever the head position, and whatever the gravitational condition, subjects performed hand movements within the same movement time (780 msec in average).

Amplitude of peak velocity

As for movement time, no significant effect of rotation and position of the head was found on the amplitude of peak velocity (p>.05). In average, amplitude of peak velocity was about 91 cm/sec whatever the head position or the amplitude and orientation of the gravitoinertial vector.

Time to peak velocity

The statistical analysis showed no main effect of rotation nor head position (global mean: 303 msec) on the moment of occurrence of the peak velocity (p>.05) confirming that the kinematic structure of the pointing movement was not influenced by rotation of the platform or by head position.

Our results suggest that having the head fixed and kept aligned with the trunk was of advantage for accuracy of pointing movements performed in such inertial conditions, without leading to modification of the kinematic features of the movements. Mechanical and inertial constraints on the moving limb being identical whatever head position during rotation of the platform, we hypothesize that normalized angular errors observed in the HU condition may be related to the deviation of the head position during the rotation of the platform.

Analysis of head position

Normalized roll angle of the head

The ANOVA showed a main effect of Rotation on the normalized roll angle of the head ($F(2,18)=13{,}54$, $p<.001$). Subjects inclined their head towards the center of rotation of about 10 degrees during PER-rotation (-9.94°) comparative to the PRE and POST-rotation which were not significantly different from each other. The modification of the head position towards the center of rotation tended to align the longitudinal axis of the head with the new gravitational vector, even if this reorientation was not complete (head inclined at 10° whereas the gravitational vector was inclined at 17°).

Normalized yaw angle of the head

The ANOVA yielded a main effect of Rotation on the normalized yaw angle of the head ($F(2,18)=21{,}63$; $p<.001$). During rotation of the platform, subjects tended to rotate their head to the left, that is towards the center of rotation (in average, 8.6°), whereas centrifugal force was directed to the right, that is towards the outside of the platform. Position of the head in yaw in PRE and POST-rotation were not significantly different ($p>.05$).

Discussion

The main objective of our study was to analyze the influence of head position on the accuracy of pointing movements towards visual memorized targets performed in modified background force level.

Our results firstly confirm previous results obtained on pointing movements towards visual targets performed in modified background force level (Bourdin et al., 2001). It appears that, whatever head position, subjects made large angular errors in the direction of the inertial forces when pointing towards visual memorized targets. The amplitude of these errors was constant during the rotation of the platform. After rotation, subjects immediately retrieved a high level of accuracy, that is the same level of accuracy than during PRE-rotation. These results firstly confirm that rotation of the platform induces perturbations in the execution of goal-directed behaviors. Moreover, our data also confirm that no adaptation of the pointing movements occurred during the rotation of the platform in complete darkness. As suggested previously (Bourdin et al., 2001; Lackner and Dizio 1998), vision of the limb seems to be a essential prerequisite for such an adaptation.

The main result of this study is that amplitude of the angular errors made during rotation of the platform depends critically on the position of the head. Changes of the position of the head relative to the body systematically influence amplitude of angular errors when subjects pointing towards memorized targets in modified background force level. Our results suggest a strong relationships between head position and angular errors when inertial forces perturb limb movements. These results are different from those of Biguer et al. (1984) obtained in a normogravity field. These authors showed that accuracy of pointing movements was higher when subjects were able to move their head than when it was maintained aligned with the trunk. In contrary, our results showed that, in modified background force level, accuracy of pointing movements was greater when the head was maintained fixed and aligned with the vertical. Our abilities to localize objects in space, orient relative to them, move toward or away from them, and reach and manipulate them depend critically on receiving, processing, and integrating spatial information from gravity, the visual field, and the observer's own body. For instance, manually reaching to a visual object presented in total darkness requires the coding of the object position in relation to the body (Jeannerod, 1988). The basic coordinate system for such a task is the egocentric frame of reference, which allows the computation of the spatial position of visual objects with respect to the observer. In the visual input-motor output chain, these egocentric coordinate systems (e.g., head-centered, body-centered) are interposed (intermediate representations) between sensory input (encoded in retinal coordinates) and motor output, such as an arm reaching movement towards a visual object. These egocentric spatial coordinates are computed through the integration of inputs from multiple sensory sources (visual, proprioceptive-somatosensory, vestibular), entailing a coordinate transformation from sensory (retinotopic) to higher-order spatial egocentric and world-center representations or frames of reference. Because of this, accuracy of targeted movements was partly dependent of the coding of head position which determined itself the spatial localization of the target. Our results showed a strong relationships between head position and amplitude of angular errors, suggesting that head position was probably not precisely coded in this particular inertial condition. This may confirm the hypothesis of an altered proprioceptive coding of limb position (and particularly of head position) suggested by previous authors (see Bock et al., 1996 for a review). Object localization in space in the absence of an external (visual, auditory, haptic) reference is known to involve a signal of head position in space derived from vestibular cues (Blouin et al., 1995) and from neck proprioceptive afferents. By considering the head as a limb, we could hypothesize that head position could be misperceived (because of the altered proprioceptive coding) leading to mislocalization of the presented targets. This suggests that the observed errors in our experiment were mainly due to this perceptive phenomenon. Our data also showed that rotation of the platform, as well as change in the position of the head did not influence the kinematic features of the pointing movements, confirming that the observed effects of rotation of the platform and of change of the position of the head on accuracy of goal-directed behaviors would have a perceptive component.

Finally, it is noteworthy that subjects made errors in performing the task with the head fixed in a vertical position. However, the errors were weaker when the subjects' head was fixed then it was free. Two hypotheses can be proposed to explain this result. Firstly, we propose that the altered proprioceptive coding of the head previously described could be responsible for the errors performed with the head fixed. As the head was kept vertical and aligned with the trunk, this perceptive distortion would have less provocative effects on the visual localization of the target and then on the accuracy of the movements. Secondly, we hypothesize that the inaccuracy of pointing movements performed during the rotation of the platform with the head fixed could reflect motor errors, in the sense of a non-adequate motor command sent to the effectors (Bock et al., 1996). Indeed, when required to point towards memorized visual targets during the rotation of the platform, subjects had to take into account the direct mechanical effect of the inertial forces on the moving limb. If not the case, the motor command could be inappropriate to the new gravitational force field, leading to inaccuracy in the execution of goal-directed movements. The existence of such motor errors had to be tested more clearly.

In conclusion, our results suggest that the observed errors in pointing movements towards memorized targets when orientation of the gravitational vector is modified may have an perceptive component. Our experiment confirms that modification of the position of the head during centrifugation may be a source of spatial disorientation. It seems plausible to propose that fixation of the head in a given position (to be defined) may reduce the emergence of spatial disorientation. Our data suggest that modification of the head position in such gravitational force field may have direct consequences on the accuracy of motor behavior when vision is precluded. For example, recent data obtained in our laboratory showed that peripheral visual information presented in total darkness during rotation of the platform induces a reorientation of the head in the direction of the visual information. On the basis of our experiment, we suggest that a peripheral visual information may allow to modulate the amplitude and the direction of the errors (depending on the orientation of the head) made in pointing movements. Specific directional effects of the head position has to be tested to confirm this hypothesis.

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Désorientation spatiale par dérives perceptives générées par certains systèmes militaires

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Summary
The development of new technologies in the weapon systems generate sensory flows that can induce sensory interactions, conflicts and dysfunction. The consequences can be pathological disorders, spatial disorientation or space confusion. Must of these problems has been studied in the field of aviation and concerned large gravito-inertial forces. However, perceptual drifts have been observed for lower gravito-inertial forces generated by antiaircraft guns. Studies of a visual tracking task have shown that low accelerations, under phenomenological thresholds of the vestibular system, unconsciously affect the spatial perception of a target. Basic studies suggest new explanations of the psychophysiological mechanisms of the vestibular system. Moreover, these data can help understand potential problems of spatial disorientation produced by low sensory stimulation.

Parmi les contraintes mentales qu'induisent certains systèmes d'armes utilisant les nouvelles technologies, les flux sensoriels qui participent à l'exécution d'une tâche, deviennent une source grandissante de problèmes. Au-delà de la charge ou de la fatigue mentale, certains systèmes sont à l'origine de phénomènes d'interactions, de conflits et de dysfonctionnements sensoriels aux effets péjoratifs sur l'efficience de ceux qui les emploient. A l'extrême, les conséquences peuvent être des troubles pathologiques de type nausées et vertiges connus depuis longtemps dans le domaine du mal des transports, des simulateurs et de la réalité virtuelle. En dehors de la pathologie, les conséquences les plus courantes générées par ces systèmes sont les illusions sensorielles, la désorientation spatiale ou encore les dérives perceptives. L'origine revient à l'instabilité et l'incohérence du flux sensoriel généré par les nouveaux équipements, mais aussi, aux propriétés fonctionnelles du Système Nerveux Central qui engendre ses propres dysfonctionnements. Dans la problématique des interactions et des conflits intersensoriels qui mettent en jeu la vision, l'oreille interne et la somesthésie, la construction perceptive de l'environnement et la représentation mentale qui en découle, prennent en compte l'ensemble des informations sensorielles. Selon les conceptions cognitivistes, le cerveau à partir des systèmes sensoriels, mémorise en permanence non seulement de l'information mais aussi et surtout de l'expérience. Ainsi, les conflits cognitifs qu'engendrent les discordances de flux sensoriels entre la vision, l'oreille interne et la proprioception, sont à l'origine des dérèglements comportementaux et des phénomènes pathologiques. Les conflits, les interactions et les dysfonctionnements sensoriels ne sont autres que des situations perceptives particulières dans lesquelles le système nerveux central traite des informations inhabituelles, discordantes ou incomplètes par rapport à l'expérience et l'expertise acquises par le sujet. Ces situations viennent ainsi déstabiliser, désorganiser des automatismes acquis avec le temps et renforcés quotidiennement.

Historiquement, les premiers effets saillants des interactions sensorielles ont été observés en aéronautique, avec les illusions dont sont l'objet les pilotes soumis à de fortes accélérations gravito-inertielles. Mais aujourd'hui, l'émergence et la multiplication de ces problèmes de conflits et d'interactions sensorielles ne se limitent pas au milieu de l'aéronautique ; ils s'observent aussi sur des systèmes d'armement terrestres que l'on pourrait qualifier à priori d'inoffensifs pour l'individu en matière de contrainte gravito-inertielle. Ainsi, des phénomènes similaires à des illusions s'observent avec des systèmes de poursuite de cible sur lesquels l'opérateur qui effectue une visée dynamique, est également l'objet d'un décalage perceptif de l'axe de visée. La particularité importante de ces situations est que l'opérateur n'est pas conscient de ce phénomène de dérive perceptive alors que les effets sont significatifs sur la performance. Ce phénomène est en fait induit par les déplacements rotatoires de l'opérateur avec la machine qu'il pilote, déplacements qui génèrent de faibles stimulations gravito-inertielles affectant l'oreille interne. En effet, par une étude sur simulateur respectant les mêmes caractéristiques de déplacement postural nous avons pu mettre en évidence un phénomène de dérive d'avance du signal de tracking qui est permanent en tangage, même pour les vitesses et

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accélérations rotatoires les plus faibles. Ce résultat est assez inattendu par rapport à l'hypothèse selon laquelle la perception des mouvements de la cible se ferait uniquement à partir d'invariants appartenant à l'organisation optique du champ visuel (Gibson, 1968, 1979). En effet, on était en mesure de penser que le traitement visuo-visuel de la cible et du réticule de pointage dépendrait essentiellement de la vitesse et de la trajectoire de la cible. De fait, la dérive du signal de tracking aurait dû être «en retard» sur la trajectoire de la cible. Par rapport aux données de la littérature, l'explication la plus cohérente pour justifier ce phénomène de dérive, se rapporte aux illusions d'origine vestibulaire. Dans le sens des rotations en tangage, il s'agirait de phénomènes similaires aux illusions d'élévation et oculogravique liées aux accélérations linéaires, radiales et tangentielles.
Cette étude sur simulateur a été complétée par des travaux fondamentaux. Le modèle expérimental utilisé consiste à faire effectuer une tâche d'ajustement de la perception visuelle du niveau des yeux. L'horizon visuel subjectif est une référence égocentrique qui permet d'estimer la localisation d'un objet au-dessus ou au-dessous de la direction du regard. L'effet de perturbations gravito-inertielles sur l'horizon visuel a été montré dans l'illusion d'élévation avec modification de l'amplitude de la gravité et dans l'illusion oculogravique avec modification de l'amplitude et de la direction de la gravité (Clark et Graybiel, 1951 ; Cohen, 1973, 1981 ; Correia et al., 1968 ; Graybiel, 1952 ; Schöne, 1964 ; Whiteside, 1961). Dans tous les cas, l'augmentation d'amplitude et/ou le déplacement de la résultante gravito-inertielle vont dans le sens d'un abaissement de l'horizon visuel. Le point commun de l'ensemble des travaux, est que les effets observés ont tous eu lieu dans des conditions de charge gravito-inertielle importante, *G* étant majoré de 25 à 100%. La démarche fondamentale entreprise à ce niveau s'intéressait aux interactions entre des stimulations posturo-gravitaires de très faible intensité comprises entre les valeurs maximum de 9,85m/s^2 et minimum de 9,810000624 m/s^2, générées par centrifugation et la PVNY (Raphel, Barraud, 1994).
Les principaux résultats (figure 1) montrent qu'en absence de référence visuelle, l'abaissement de l'horizon visuel devient significatif à partir d'une accélération radiale de 0.014m/s^2 (Gi=9.81001m/s^2). Cette valeur est inférieure à la plus basse des valeurs (environ 0,05 m/s^2), du seuil de perception phénoménologique d'une accélération linéaire connu à ce jour (Boff et Lincoln, 1988). Ainsi, dans la tâche de tracking décrite précédemment, la dérive du signal semble bien résulter d'un phénomène assimilable à une illusion oculogravique, totalement inconsciente pour le sujet. Par ailleurs, il existe une relation logarithmique entre l'accélération radiale de faible intensité et l'abaissement de l'horizon visuel.

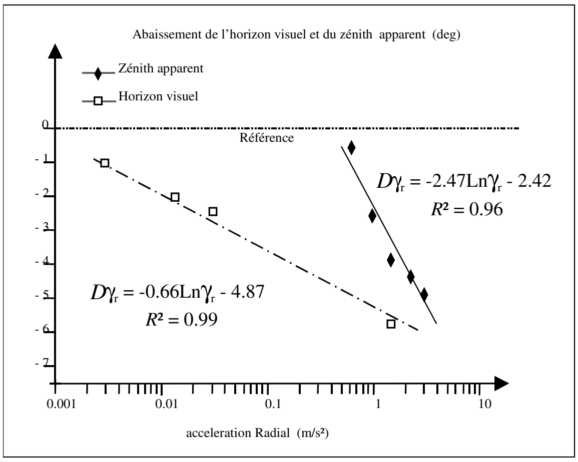

Figure 1 : Représentation graphique de la fonction de régression logarithmique entre l'accélération radiale et l'écart d'ajustement de l'horizon visuel (Raphel et Barraud, 1994) et du zénith apparent (Raphel et al., 2001).

Les mécanismes à l'origine de cet abaissement de l'horizon visuel sont expliqués de manière phénoménologique par une perception illusoire d'inclinaison arrière en tangage du corps semblable à celle observée lorsque le sujet est soumis à de fortes accélérations linéaires. Au niveau physiologique l'abaissement de l'horizon visuel serait expliqué uniquement par les actions mécaniques des stimulations au niveau otholithique. En effet, lorsque la résultante gravito-inertielle est importante la stimulation intéresse les capteurs vestibulaires ainsi que la proprioception mécanoréceptrice. Par contre, lorsque les accélérations radiales sont faibles, seuls les détecteurs otolithiques d'accélération linéaire sont mis en jeu puisque les faibles variations de la résultante gravito-inertielle exclu une origine tactile et kinesthésique sachant que les variations du poids du sujet sont de l'ordre de quelques centaines de milligrammes.

Dans le but de caractériser la contribution de l'organe otolithique à l'élaboration de l'horizon visuel, nous avons entrepris une étude des effets des accélérations radiales de faibles intensités produites par centrifugation lorsque le sujet est en position couchée dans le noir (Raphel et al., 2001). Par rapport au système de poursuite de cible à l'origine de ces travaux, cette position représente l'inclinaison en tangage maximum que le sujet peut subir. Dans cette position, la perception visuelle du niveau des yeux correspond au zénith apparent et donc à la direction gravitaire (figure 2). Le système vestibulaire a subit une rotation de 90° par rapport à la force gravitaire. Les forces de centrifugation et gravito-inertiel qui s'exercent sur le système otolithique sont donc inversées. Les principaux résultats montrent un abaissement significatif du zénith apparent par rapport aux ajustements à l'arrêt lorsque le sujet couché est soumis à une contrainte de centrifugation (figure 1). Ainsi, quelle que soit la position spatiale du sujet, l'accélération radiale induit un déplacement de l'horizon visuel semblable au déplacement de la résultante gravito-inertielle. Par ailleurs, s'il existe une relation logarithmique entre les accélérations et l'abaissement du zénith apparent semblable à celle observée en position assise, les valeurs des constantes sont différentes. Le seuil théorique de sensibilité aux accélérations est plus élevé en position couchée qu'en position assise. La sensibilité aux variations d'accélération est également plus élevée dans la position couchée.

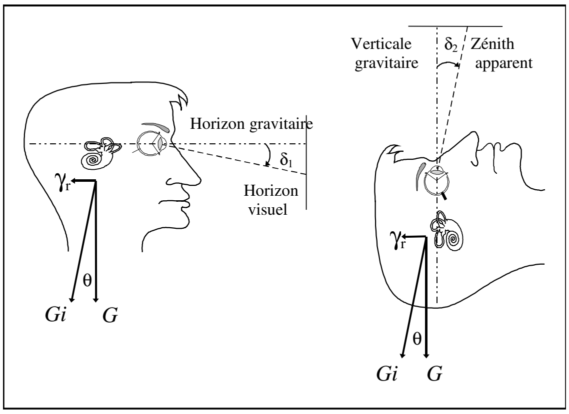

Figure 2 : Représentation des effets perceptivo-moteurs des forces agissant sur l'oreille interne au cours du déplacement postural du sujet en position verticale et horizontale.

Une explication strictement sensorielle liée aux variations fonctionnelles des propriétés neurophysiologiques des différents capteurs otolithiques ou en termes d'effets combinés du système vestibulaire et de la proprioception oculaire ne semble pas suffisante pour expliquer la contradiction fonctionnelle entre un seuil perceptif bas associé à une faible sensibilité aux variations d'accélération dans la position assise, et un seuil perceptif élevé associé à une sensibilité élevée aux variations d'accélération dans la position couchée. Les différences de sensibilité entre la position assise et couchée peuvent trouver une explication dans un modèle écologique de fonctionnement de l'oreille interne. Selon ce modèle, la pertinence, l'intégration et le traitement mental des signaux sensoriels dépendraient des conditions dans lesquelles les organes sensoriels sont habituellement mis en jeu. Dans la vie courante, pour un sujet en position érigée, le système otolithique est activé par les mouvements antéro-postèrieures de la tête pour des accélérations comprises entre 0 et plusieurs m/s^2. Dans ces conditions, le seuil de détection des signaux vestibulaires devrait être bas et la sensibilité aux variations des accélérations linéaires devrait être faible compte tenu de l'étendue des accélérations possibles. Dans l'axe vertical, le système otolithique est par contre toujours soumis à la gravité et les variations de la force gravitaire sont faibles. Dans ces conditions, on peut comprendre que le seuil de détection des accélérations linéaires dans l'axe vertical soit élevé et que la sensibilité aux variations d'accélération dans la direction gravitaire soit également élevée. C'est ce que nous observons effectivement lorsque le sujet couché subit une accélération linéaire sur un axe inféro-supérieur.
Enfin, il faut noter que, quelle que soit la position spatiale du sujet, si l'accélération radiale induit un déplacement de l'horizon visuel semblable au déplacement de la résultante gravito-inertielle, cette adéquation est loin d'être homothétique en matière de déplacement angulaire dans le plan horizontal. En effet, pour une inclinaison de la résultante gravito-inertielle inférieure à 1.95°, la réponse visuelle est amplifiée puisque le déplacement de l'horizon visuel est beaucoup plus important que le déplacement de la résultante gravito-inertielle (figure 3). Au-delà de 9.6° d'inclinaison de la résultante gravito-inertielle, le déplacement de l'horizon visuel correspondant est plus faible d'où une atténuation de la réponse visuelle. Ainsi l'amplification du signal sensoriel pour les très faibles stimulations pourrait être une porte d'entrée explicative dans certaines interactions sensorielles comme le mal des simulateurs, pour expliquer en

particulier le paradoxe entre l'évolution des simulateurs qui sont technologiquement de plus en plus près de la réalité, sans toutefois être la réalité, et l'augmentation du taux des troubles fonctionnels qu'ils génèrent.

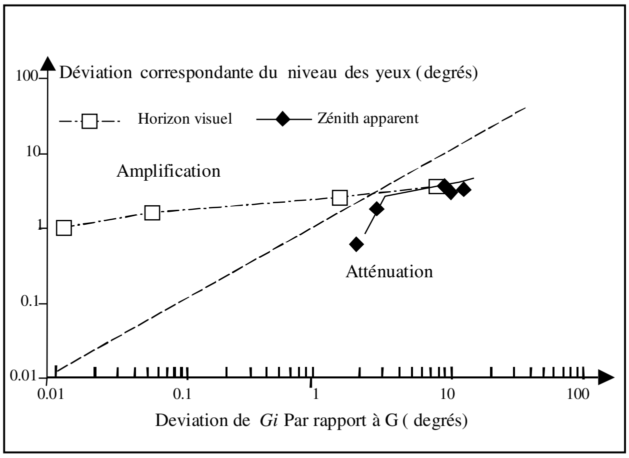

Figure 3: Représentation de la relation entre l'inclinaison de la résultante gravito-inertielle et le déplacement de l'horizon visuel et du zénith apparent. Les échelles sont logarithmiques.

En conclusion, les travaux que nous avons menés dans le domaine de l'horizon visuel, ont mis en évidence le rôle important joué par de très faibles stimulations otolithiques dans la perception spatiale d'une cible visuelle. Ces recherches en laboratoire nous permettent aussi d'expliquer la dérive du signal observée pour des stimulations posturo-gravitaires de très faible intensité lors de tâches de tracking. On peut suggérer que cette dérive perceptive résulte d'un phénomène assimilable à une illusion oculogravique, dont la caractéristique importante est qu'elle est totalement inconsciente pour le sujet.

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USAF Spatial Disorientation Survey

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SUMMARY

A recent review of mishaps by the Air Force Safety Center (AFSC) determined that spatial disorientation (SD) was implicated in 20.2% of the Class A mishaps in the United States Air Force (USAF) between 1991 and 2000, at a cost of $1.4 billion and 60 lives[8]. However, mishap data only provide limited information about the impact of SD on air operations and, as aircraft losses are relatively infrequent, do not allow detailed analysis of SD by aircraft type. A more thorough understanding of how SD affects aircrew in day-to-day flying would allow appropriate countermeasures to be developed to reduce its impact. A survey was conducted and distributed USAF-wide by flight safety officers. The survey collected data about the incidence of a wide range of SD illusions experienced in the respondents' current aircraft type. Additional information about the most recent SD incident was also collected and analyzed. Data from 2582 completed surveys were analyzed, covering 2.17 million flying hours in 34 currently flown aircraft types. The top three causes of SD for each aircraft stream were: Fast Jet (FJ) – the leans, atmospheric blending of earth and sky, and misjudged position in night formation trail; Multi-Engine (ME) – black-hole approach, sloping horizon, and the leans; Trainer (TR) – the leans, atmospheric blending of earth and sky, and Coriolis illusion; and Rotary-Wing (RW) – undetected drift, misleading altitude cues, and brownout/whiteout. The incidence and severity of SD were related to aircraft stream with FJ and RW pilots being affected most. Overall, 8% of surveyed pilots had experienced a severe episode of SD adversely affecting flight safety. Experienced aircrew, as well as those that had received previous in-flight training, reported more illusions suggesting that these factors helped with recognition of SD in flight. Despite being a regular topic at flight safety briefings, pilots still frequently experience SD sufficient to impair performance. This USAF-wide SD survey identifies problem areas for pilots of different aircraft types, which should allow training and research to be targeted more effectively in future. However, with the advent of helmet-mounted displays, greater use of night vision devices, and increasing aircraft agility/performance, SD related mishaps will continue to pose a significant threat to aircrew. Innovative technological solutions may be required to prevent an increase in SD related mishaps.

INTRODUCTION

Much of what is known about the incidence of SD is derived from published surveys of aircraft mishap data. The SD mishap rate, as a percentage of all aircraft mishaps, has varied widely in these surveys, ranging from 2.5% to 30.8% in different aircrew populations[2-5,12,13,16,18,19,21,22,27-29]. A number of factors are responsible for this wide variation. Firstly, SD mishaps have a high fatality rate and the role that SD may have played in the mishap can often only be inferred from circumstantial evidence. In light of this, mishap Boards of Inquiry have not always been consistent in considering SD as a causal or contributory factor in mishaps. Furthermore, mishap surveys have used a variety of definitions for SD, with profound consequences on the SD-attributable rate[21]. However, few would doubt that SD is a significant flight safety

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issue and, despite a fall in aviation mishap rates overall, recent figures for SD-attributable mishap rates show no significant decrease over the past 3 decades. In the 10-year period between 1991 and 2000, SD was a causal or major contributory factor in 20.2% of USAF Class A mishaps at a cost of $1.4B and 60 aircrew lives[8]. These figures are consistent with recent reports from the US Army and USN that have shown SD to contribute to 27% and 26% of mishaps, respectively, with a fatality rate 3 times that of non-SD accidents[11,15]. However, although mishap surveys have been valuable in raising awareness of SD as a problem in the aviator community, they reveal little about the frequency with which pilots are affected by SD or the effect SD has on their performance.

Previous surveys of the incidence of SD in pilots have frequently been confined to pilots flying a restricted range of aircraft types, while others have only looked at specific types of SD (Table 1). Furthermore, as with the mishap surveys, a variety of definitions of SD have been used, thereby making it difficult to compare the results from one survey with those of another. Over time, changes in flight symbology, aircraft performance, and pilots' SD training may also be expected to have an effect on the incidence of SD, making it difficult to apply the findings of past studies to pilots flying aircraft currently in service.

Author	Years	Survey Group	Comment
Clark (1971)[6]	1970	336 USN, US Army & USAF pilots. All main aircraft types	
Tormes & Guedry (1975)[26]	1974	104 USN helicopter pilots	
Steele-Perkins & Evans (1979)[25]	1978	182 RN helicopter pilots	
Lyons & Simpson (1989)[17]	1986-87	97 USAF tactical aircrew	Survey of giant hand phenomenon only
Kuipers et al (1990)[14]	-	209 RNLAF fighter pilots (NF5 and F16)	
Navathe & Singh (1994)[20]	1989-90	413 Indian Air Force pilots. All main aircraft types	
Durnford (1992)[9]	1991	338 UK Army pilots. Almost exclusively helicopter pilots	
Collins & Harrison (1995)[7]	1992	96 USAF F-15C Desert Storm pilots	Single aircraft type
Braithwaite et al (1998)[4]	1993	299 US Army helicopter pilots	
Sipes & Lessard (2000)[23]	1997-98	141 USAF pilots attending the Advanced Instrument School. All main aircraft types	
Sixsmith (2001)[24]	2001	92 RAF/UK Army pilots. All main aircraft types.	Survey of break-off phenomena (giant hand and detachment) only

Table 1. Surveys of pilots' experiences of SD

This paper describes a USAF-wide questionnaire-based survey of pilots aimed at establishing the current incidence and severity of SD in a wide variety of USAF aircraft types. The questionnaire was developed with the hope that it could be used as a standardized tool that could be used to track changes in the incidence of SD over time and across different aircrew populations. In this way, it could be used to identify the effectiveness of new SD countermeasures.

METHOD

Questionnaire Design and Distribution

A two-page questionnaire based on that used by Sipes and Lessard[23] was developed to collect anonymous data from pilots regarding their experience of SD in their current aircraft types. However, whereas Sipes and Lessard recorded the pilots' total count of various illusions in their two most recent aircraft types, this study looked at the frequency of individual illusions that were being experienced only in the pilots' current aircraft type. Questions addressed pilot characteristics; previous SD training; experience of specific illusions/factors contributing to SD, and details of the pilots' most recent SD incident. The questionnaire was field-tested on 60 students attending the USAF Advanced Instrument School at Randolph AFB, Texas. The questionnaire was subsequently distributed electronically by the US Air Force Safety

Center (AFSC) to all Flight Safety Officers and was administered at a squadron flight safety meeting. In order to get some idea of the response rate, the Flight Safety Officers were asked to coordinate the returns and submit a return rate for their particular squadrons. Questionnaires were completed anonymously.

For the purposes of this survey, a modified version of the Air Standardization Coordinating Committee's Working Party 61 (ASCC WP61) definition of SD was used:

An incorrect perception of linear/angular position, or of motion, relative to the Earth's surface or another aircraft, SUFFICIENT TO AFFECT PERFORMANCE, SITUATIONAL AWARENESS OR WORKLOAD – HOWEVER SLIGHT THAT EFFECT MAY BE.

It was considered desirable to collect data only on SD incidents that had a perceived impact on performance, situational awareness or workload, as these have a potential impact on flight safety and are of concern to aircrew.

For each of the specific illusions/factors listed in the questionnaire, a short description was given in terms that pilots could readily understand, similar to that of Sipes and Lessard[23]. Information about the pilots' most recent SD incident was collected using pick-lists for time since last SD; phase of flight, weather conditions; illumination level; terrain type; visual aids, and severity. There was also a space for the pilot to record a description of the incident, what caused it, and how recovery was carried out. Only time since last SD and severity were analyzed for this paper.

Following presentation of early preliminary results at an ASCC WP61 meeting in November 1999, the survey, with minor modifications, was subsequently adopted as a standardized tool for collecting data on the incidence of SD in flight[1]. Researchers in the UK have recently used this to look at the incidence of SD both in fixed- and rotary-wing aircrew[10].

Between Aug 99 and Jan 00, 2582 questionnaires were returned and their data were entered on an *MS Access* database for analysis. Individual aircraft types were categorized as Fast Jet (FJ), Multi-Engine (ME), Trainer (TR) and Rotary Wing (RW) in order to enable comparisons to be made with data obtained from the survey being conducted on UK aviators using a near-identical questionnaire. The classification of USAF aircraft used in this paper is shown in Table 2.

Aircraft Stream	Aircraft Types
Fast Jet (FJ) (n=468)	A-10 (n=26), F-15 (n=123), F-16 (n=313), F-117 (n=6)
Multi-Engine (ME) (n=662)	B-1 (n=6), B-2 (n=1), B-52 (n=4), C-5 (n=52), C-9 (n=42), KC-10 (n=28), C-12 (n=5), C-17 (n=11), C-20 (n=1), C-21 (n=57), C-130 (n=198), MC-130 (=25), AC-130 (n=23), C-135 (n=6), KC-135 (n=154), RC-135 (n=1), C-141 (n=47), Boeing 737 (n=1)
Trainer (TR) (n=1288)	T-1 (n=147), T-3 (n=1), T-37 (n=750), T-38 (n=336), AT-38 (n=49), BE-40 (n=3), Piper (n=1), Cessna-150 (n=1)
Rotary Wing (RW) (n=101)	HH-60 (n=14), MH-53 (n=26), UH-1 (n=61)
Not Determined (n.=63)	-

Table 2. Classification of USAF aircraft.

The severity of the most recent and worst-ever SD incidents used the same classification as that used by Durnford and Braithwaite in their surveys of SD in helicopter pilots[4,9]:

Minor – Flight safety not at risk
Significant – Flight safety not at risk but could have been jeopardized under different conditions
Severe – Flight safety was at risk

Statistical Analysis

Statistical analysis was performed to investigate the effects of the main independent variables: age, crew position, total hours flown, aircraft type, and hours-on-type. Controlling for these factors, the effects of training frequency, training type, rating of training, and trainer (flight surgeon, physiologist, pilot or other) on the dependent variables were also considered. The factors, factor type, and levels used in the analysis are listed in Tables 3 and 4. Due to the skewed distribution of the responses towards 'never' and 'rarely', the responses were weighted as follows: 0 for 'never' and 1 for 'rarely or above'.

The dependent variables comprised the frequency of illusions (combined and in separate categories) and the rated severity of the most recent and worst ever SD experience (see Table 5). The display illusions were analyzed together as a group and with HUD-related SD and NVG-related SD on their own. As the miscellaneous illusion category could not be logically grouped together, it was decided to analyze the group as three separate items: giant hand/detachment; SD due to task saturation (distraction), and SD due to poor crew coordination.

Variables	Type	Levels
Age	Covariate	
Crew Position	Factor	Student Pilot, Pilot, Instructor Pilot
Total Hours Flown	Covariate	
Aircraft Stream	Factor	Trainer, Multiengine, Fast-jet, Rotary, Not Specified
Hours-on-type	Covariate	

Table 3. Main independent variables used in the analysis

Variables		Type	Levels
Frequency of training (months)		Factor	<6, 6-12, >12-24, >24-48, >48
Type of training:	In-Flight	Factor	Not Given, Given, Not Specified
	Ground Demo	Factor	Not Given, Given, Not Specified
	Lecture	Factor	Not Given, Given, Not Specified
Rating of training		Covariate	
Trainer		Factor	Flight Surgeon, Physiologist, Pilot, Other

Table 4. Training independent variables used in the analysis

No.	Variables	Type	Levels
1	All illusions	Factor	Principal Component
2	Visual illusions	Factor	Principal Component
3	Nonvisual illusions	Factor	Principal Component
4	Displays illusions	Factor	Principal Component
5	Central psychological (giant hand & detachment)	Factor	No=0, Yes=1
6	Distraction due to task saturation	Factor	No=0, Yes=1
7	Poor crew co-ordination	Factor	No=0, Yes=1
8	HUD illusions	Factor	No=0, Yes=1
9	NVGs illusions	Factor	No=0, Yes=1
10	Severity of most recent SD experience	Factor	Never/minor=0, Significant=1, Severe=5
11	Severity of worst ever SD experience	Factor	Never/minor=0, Significant=1, Severe=5

Table 5. Dependent variables used in the analysis

The dependent variables 1-4 in Table 5 are the results of applying a principal component procedure to obtain a single measure to describe the effect. The natural logarithms of total flying hours and hours-on-type terms were used in the analysis. Variables were selected from the possible combinations (age, crew position, total hours flown, aircraft type, hours-on-type, frequency of training, type of training, rating of training and trainer) by a 'stepwise' method. A multiple analysis of variance was used, with a significance criterion of $p < 0.05$. In cases of significance, post-hoc tests (Scheffe and Bonferroni) were performed to identify the source of any significant effects within each factor.

RESULTS

Although it was not possible to find out how many of the USAF's 12,000+ pilots received a questionnaire, many Flight Safety Officers provided return rate data for their particular squadrons. Of the 2582 responses, 40.7% were returned from squadrons with a return rate >50%, 18.1% came from squadrons with a return rate <50% and squadron return-rate data were not available for 41.2% of responses. There was no significant difference in the reporting of SD between questionnaires from squadrons with a return rate >50% and those from squadrons with a return rate of <50%.

The demographic data showed that respondents' age distribution was similar to that of the USAF pilot cadre in general, but with an over-representation of pilots aged 22-25, corresponding to a high return rate amongst student pilots. The mean age of respondents was 30.9 yrs (sd 6.5 yrs). Overall, pilots recorded a mean total flight time of 1815 hrs (sd 1677 hrs) with 842 hrs (sd 1007 hrs) being spent on their current aircraft types – a total flight time of 2.17M hrs on current type for analysis. Almost all aircraft types were represented, with significant returns from each of the principal aircraft streams (FJ, ME, TR and RW).

Respondents reported receiving some form of SD training, with a mean frequency of 17.6 months (SD = 13.89 mo). Most of this training was provided by physiologists (51.5%), but with pilots also being actively involved (32.9%). Flight Surgeons were not actively involved in SD training, delivering just 2.1% of pilots' most recent SD training. The percentages for previous experience of SD training by lecture, ground demonstration, and in-flight demonstration were 84.7%, 78.7% and 58.3%, respectively. Only 0.3% of pilots could not recall having received any SD training. Data on pilots' previous experiences with SD training showed that pilots were generally happy with the training they had received, with 92.9% of pilots rating their training satisfactory or better (see Fig. 1).

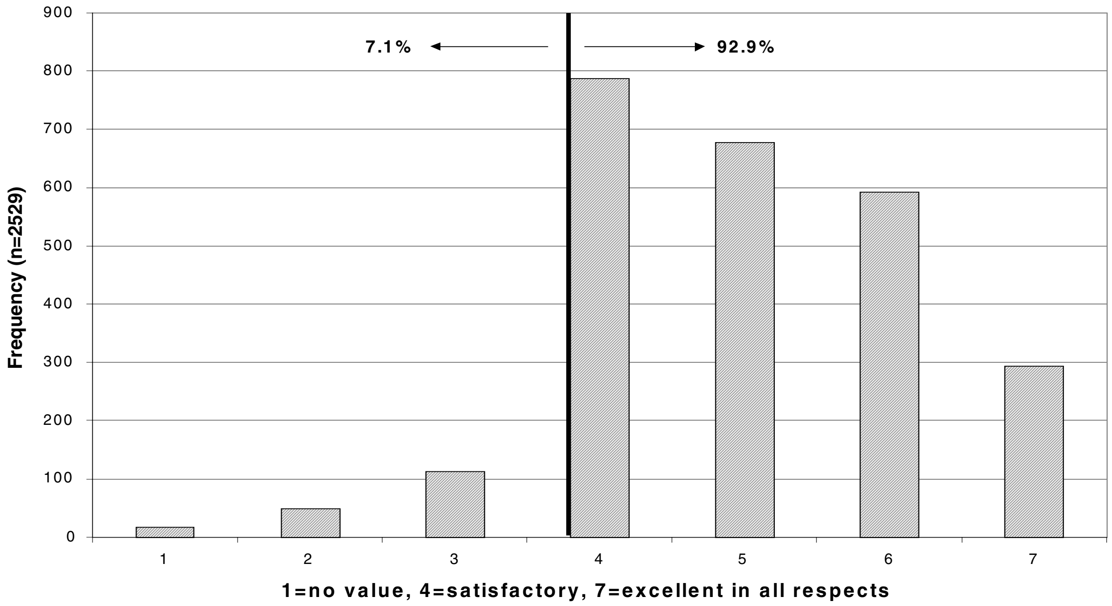

Figure 1. Pilot satisfaction with SD training

The frequency distributions for each of the specific SD illusions described on the questionnaire for all aircraft types are shown in Figs 2-5. The following terms were used to describe frequency: "rarely" (experienced only once or twice in current aircraft type), "seldom" (encountered in <5% of all sorties), "occasional" (<25% of all sorties), and "frequent" (>25% of all sorties).

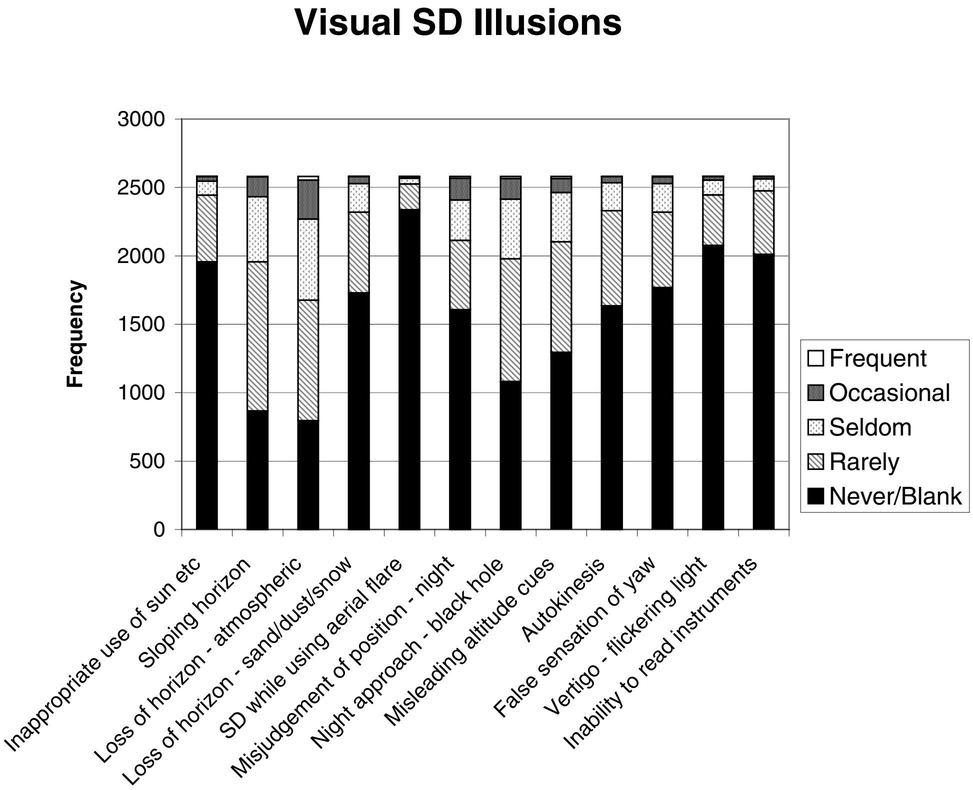

Figure 2. Frequency distribution of visual SD illusions/factors.

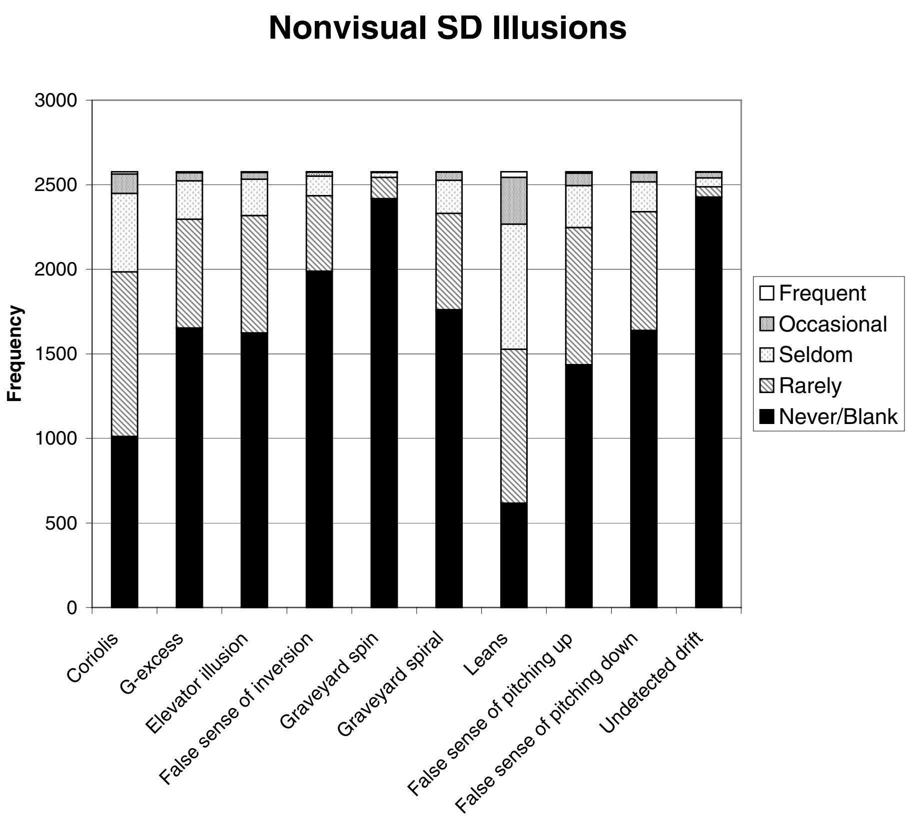

Figure 3. Frequency distribution nonvisual illusions/factors

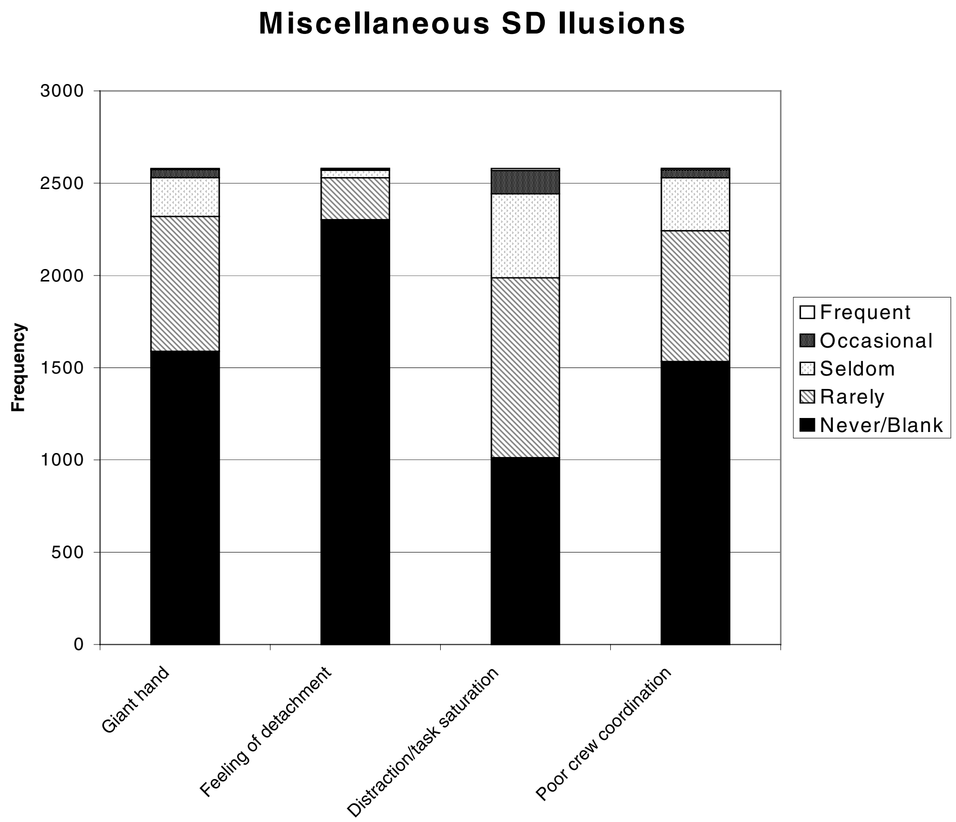

Figure 4. Frequency distribution of miscellaneous SD illusions/factors

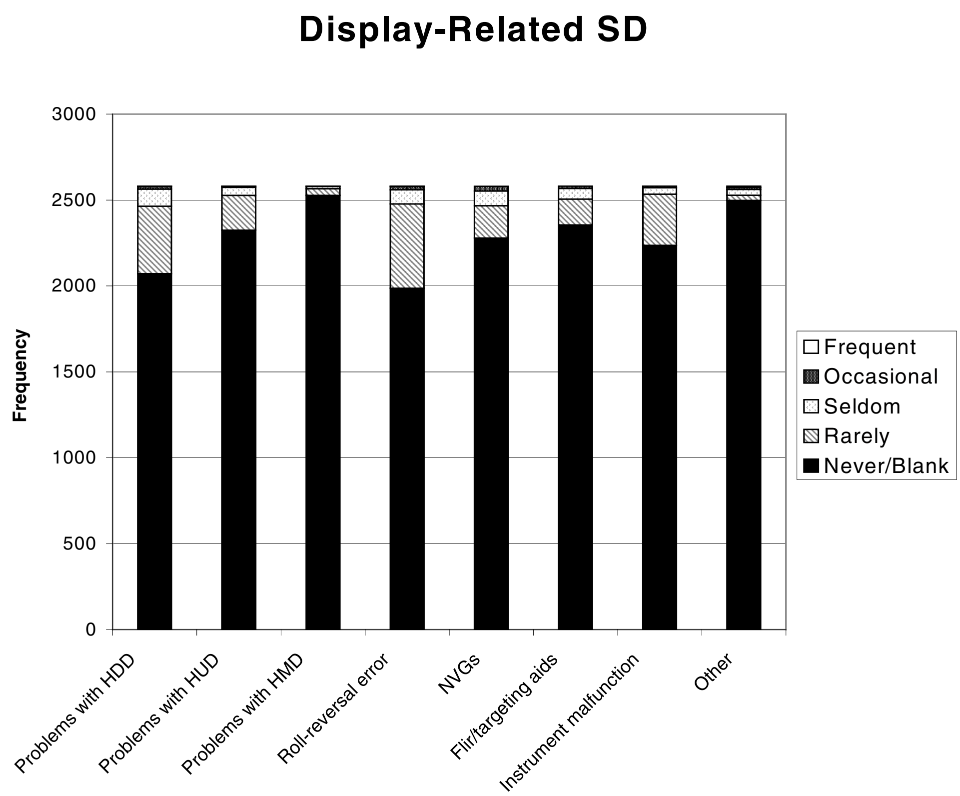

Figure 5. Frequency distribution of display-related SD illusions/factors

On average, pilots reported having experienced 10.6 of the 34 possible SD illusions or situations listed on the questionnaire. Only 6% of pilots reported no episodes of SD in their current aircraft type and most of these were student pilots with limited flying hours. The frequency with which each description of SD was reported, broken down by main aircraft type, is shown at Table 6.

Abbreviated Description (Ranked by % of all pilots reporting SD incident)	% Reporting at least 1 incident				
	All	FJ	ME	TR	RW
Leans	76.0	83.8	74.5	74.5	75.2
Loss of horizon – atmospheric	69.2	78.4	71.9	64.8	66.3
Sloping horizon	66.4	71.6	78.5	58.4	65.3
Coriolis	60.8	62.2	59.4	62.3	42.6
Distraction/task saturation	60.7	64.7	68.2	55.3	60.4
Night approach – black hole	58.1	65.2	82.6	42.4	57.4
Misleading altitude cues	49.8	64.7	58.9	37.2	80.2
False sense of pitching up	44.3	53.4	45.3	42.3	19.8
Poor crew coordination	40.5	18.6	60.9	35.4	68.3
Giant hand	38.4	40.8	37.7	36.5	55.4
Misjudgment of position – night	37.8	75.0	55.2	15.3	37.6
Elevator illusion	37.1	37.0	37.6	37.1	31.7
Autokinesis	36.7	40.8	51.9	25.9	45.5
False sense of pitching down	36.5	47.6	37.0	33.8	17.8
G-Excess	35.9	53.2	21.2	39.4	13.2
Loss of horizon – sand, dust, snow	33.0	41.0	42.8	21.4	76.2
Graveyard spiral	31.7	31.4	31.8	31.3	38.6
False sense of yaw	31.5	38.7	41.6	24.5	25.7
Inappropriate use of sun etc	24.2	35.9	26.0	18.9	22.8
Roll-reversal error	23.0	20.3	21.8	24.2	25.7
False sense of inversion	22.9	27.8	20.0	23.4	12.9
Inability to read instruments	22.1	19.2	18.0	25.8	18.8
Problems interpreting head-down display	19.8	27.8	22.4	14.8	22.8
Flicker vertigo	19.6	22.9	23.3	15.1	36.6
Instrument malfunction	13.4	14.5	14.5	10.9	18.8
SD while using night vision goggles (NVGs)	11.7	13.7	17.6	3.3	72.3
Detachment	10.8	6.6	13.5	10.9	11.9
Problems interpreting head-up display (HUD)	9.9	38.0	3.0	4.0	1.0
SD using aerial flare	9.5	17.7	7.1	7.1	12.9
SD using forward looking infra-red (FLIR)/targeting aids	8.8	24.1	5.6	2.7	32.7
Graveyard spin	6.3	4.3	2.4	9.2	1.0
Undetected drift	5.9	2.4	1.5	3.0	90.1
Other	3.3	5.6	2.7	2.6	3.0
Problems interpreting helmet mounted display (HMD)	2.1	2.8	2.6	1.5	0

Table 6. Rank Order of the Most Frequently Experienced Illusions

Overall, the most frequently encountered visual causes of SD were sloping horizon, atmospheric blending of earth and sky, black-hole approaches, and misleading altitude cues. Similarly, the principal nonvisual types of SD were the leans, the Coriolis illusion and the G-excess illusion. However, the most frequently reported disorienting condition for helicopter pilots was undetected drift (90.1%). Among the miscellaneous illusions/factors, task saturation was the most frequently reported problem. In addition, poor crew coordination and the giant hand phenomenon were experienced by 40.5% and 38.4% of all pilots, respectively. Few pilots reported problems with display- related SD. However, it should be noted that only 22.8% of all pilots responding to this questionnaire had flown with aircraft with head-up displays (HUD) capable of displaying primary flight reference symbology - of these, a much larger percentage (38%) reported problems interpreting spatial orientation information on the HUD. Similarly, only a small percentage (11.2%) of all surveyed pilots reported SD problems with night vision goggles (NVGs), RW pilots were presumably most likely to fly with NVGs and 72.3% of these pilots reported SD while using these devices in flight. Although they are not yet in service, a question regarding helmet-mounted displays

(HMDs) was included in the survey for future use. The small number of pilots reporting problems with HMDs, therefore, erroneously completed that part of the survey. This gives an indication of the error rate that may apply to other illusions (2.1%). A similar error rate of 1.9% was found by looking at reports of undetected drift among non-RW pilots.

Although Figures 2-5 give overall results for all aircraft types combined, Table 6 gives details of the types of illusions being reported most frequently by pilots in each main aircraft stream. The top three illusions for each major aircraft stream were as follows:

FJ: 1) the leans; 2) atmospheric blending of earth and sky; and 3) misjudged position in night formation trail.
ME: 1) black hole approach; 2) sloping horizon; 3) the leans.
TR: 1) the leans; 2) atmospheric blending of earth and sky; and 3) Coriolis illusion
RW: 1) undetected drift; 2) misleading altitude cues; and 3) brownout/whiteout.

Although fixed-wing pilots of all aircraft tended to experience similar illusions, the SD experience of helicopter pilots was found to be fundamentally different.

Additional information was obtained about the respondents' most recent SD incident. 26.9% of pilots had experienced SD in the month prior to the survey, and 58.2% of pilots had experienced SD in the previous six months. Most of these incidents were minor in nature; only 0.7% were judged to be 'severe' and a further 10.6% were considered 'significant'. Pilots were also asked to rate the severity of their worst SD incident in their current aircraft type. Overall, 8.2% of pilots reported having experienced a 'severe' episode of SD and a further 32.3% reporting previous incidents of 'significant' SD. There were large difference based on the pilots' aircraft stream, as shown in Table 7.

	FJ		**ME**		**TR**		**RW**	
	Recent	**Worst**	**Recent**	**Worst**	**Recent**	**Worst**	**Recent**	**Worst**
Minor	72.9%	29.3%	74.1%	32.9%	70.6%	40.1%	61.2%	23.5%
Significant	16.4%	43.1%	10.5%	38.1%	8.1%	25.3%	21.4%	41.8%
Severe	1.6%	14.4%	0.5%	5.8%	0.5%	6.7%	2.0%	19.4%
Not Recorded	9.1%	13.1%	15.0%	23.2%	20.9%	27.9%	15.3%	15.3%

Table 7. Severity of SD incidents by aircraft stream.

Statistical Analysis

Table 8 provides an overview of the results from the statistical analysis of the survey data. As illustrated, it shows that factors that influenced the susceptibility to SD were mainly aircraft type, whether in-flight training had been received, total flying time, and hours-on-type. Crew position, ground-based training, and which professional type provided the training had no significant effect on pilots' experiences of SD.

All Illusions Combined

Analysis of all SD illusions combined revealed that FJ pilots reported significantly more SD than ME or TR pilots ($p<0.01$). Pilots who had received in-flight SD training reported more SD overall than those who had not received any in-flight training ($p < 0.01$). Total flying time and hours-on-type were positively associated with pilots' experience of all SD illusions combined ($p < 0.0001$).

Visual illusions

FJ pilots experienced more visual SD illusions than did TR or ME pilots ($p<0.001$ and $p<0.01$ respectively). There were more visual SD illusions experienced by pilots who had received in-flight training compared to those who had not ($p < 0.0001$). Total flying time and hours-on-type were positively associated with pilots' experience of all visual SD illusions combined ($p <0.0001$) while rating of training was negatively correlated with visual SD illusions ($p<0.05$), indicating that pilots who rated their training highest were least likely to report visual illusions.

Nonvisual Illusions

FJ pilots reported more nonvisual illusions than either RW pilots (p < 0.01) or ME pilots (p<0.001), and TR pilots reported more of these illusions than ME or RW pilots (p<0.001 and p<0.01 respectively). Pilots who had received in-flight training reported more nonvisual illusions than those who had not received in-flight training (p < 0.0001). Hours-on-type was positively correlated with experience of nonvisual SD illusions (p < 0.0001).

Miscellaneous SD

Pilots who received in-flight training reported more incidents of giant hand/detachment and SD associated with task saturation than pilots who had not received this training (p<0.001 and p<0.0001 respectively). In-flight training was not associated with SD arising from poor crew coordination. The linear covariate hours-on-type was positively associated with all of the miscellaneous SD (giant hand/detachment and task saturation p<0.0001, crew coordination p<0.05), while total flying hours was positively associated only with crew coordination (p<0.001). Age was negatively associated with pilots reporting giant hand/detachment illusions (p<0.05). Aircraft type was associated with crew coordination SD, with FJ pilots recording fewer incidents than pilots of all other aircraft types (p<0.001) and TR reporting less SD related to crew-coordination problems than ME or RW pilots (p<0.001). RW pilots reported more giant hand/detachment illusions than ME pilots (p<0.01), but there were no other significant effects of aircraft type.

Dependent Variables	**Fixed Variables**					
	Age	**Training - Rating**	**In-flight Training**	**Aircraft Type**	**Total Flying Hours**	**Hours on Type**
All Illusions			Given>Not Given****	FJ>TR**, ME**	+ve**	+ve****
Visual		-ve*	Given>Not Given****	FJ>TR***,ME**	+ve****	+ve****
Nonvisual			Given>Not Given****	FJ>RW** FJ>ME*** TR>ME*** TR>RW**		+ve****
Giant Hand/ Detachment	-ve*		Given>Not Given***	RW>ME**		+ve****
Task Saturation			Given>Not Given****			+ve****
Crew Coordination				ME>FJ*** ME>TR*** TR>FJ*** RW>FJ*** RW>TR***	+ve***	+ve*
Display – All	+ve****	-ve*	Given>Not Given****	RW> ME***,TR*** FJ>ME*** FJ>TR***	+ve****	
HUD	+ve****			FJ>RW*** FJ>ME*** FJ>TR***		
NVG			Given>Not Given*	RW>FJ*** RW>ME*** RW>TR*** ME>TR*** FJ>TR***		+ve****
Most Recent SD				RW>ME*, TR** FJ>ME*,TR**		
Worst SD		-ve**		RW>ME*** FJ>ME*** TR>ME**	+ve****	

Table 8. Summary of results from the statistical analysis of survey data (*p<0.05, **p<0.01, ***p<0.001, ****p<0.0001)

Display Related SD - All

FJ and RW pilots experienced more display-related SD than ME or TR pilots ($p<0.001$). Age and in-flight training were positively associated with display-related SD ($p<0.0001$), while rating of training was negatively associated with reports of display-related SD ($p<0.05$).

HUD Illusions

FJ pilots reported more HUD-related SD illusions than did ME, RW and TR pilots ($p<0.001$). Increasing age was positively associated with experience of HUD-related SD illusions ($p<0.0001$).

NVG Illusions

Aircraft type had a significant effect on the reported incidence of NVG-related SD. RW pilots reported more NVG-related SD than FJ, ME, and TR pilots ($p<0.001$). FJ and ME pilots also reported more NVG related SD than TR pilots ($p<0.001$). The linear covariate hours-on-type was positively associated with the reported incidence of NVG illusions ($p<0.0001$).

Severity of Pilots' Most Recent SD Incident

The severity of pilots' most recent SD incident was significantly higher in the FJ and RW groups than in the ME and TR groups (FJ and RW>ME – $p<0.05$, FJ and RW> TR – $p<0.01$).

Severity of the Pilots' Worst SD Incident

As with pilots' most recent SD incident, there was an effect of aircraft type. ME pilots' worst experience of SD was significantly less severe than that of all other pilots (RW – $p<0.001$, FJ – $p<0.001$, TR – $p<0.01$). Total flying hours was positively correlated with severity of the worst SD incident ($p<0.0001$), while rating of training was negatively correlated ($p<0.01$).

DISCUSSION

In order to achieve a high return rate on this postal survey, it was not possible to ask questions in as much detail as would have been possible with a researcher-administered questionnaire. Nonetheless, this survey obtained important basic information about SD training and type of SD experience in a wide variety of aircraft types.

Pilot experience was found to be a strong predictor for reporting SD incidents, with hours-on-type and total flying hours being positively associated with reports of SD. To some extent, this was because pilots with more experience had more opportunity to experience SD than their peers with fewer hours. However, experienced pilots also tended to report a higher frequency of each SD illusion, which was independent of the total number of aircraft sorties flown on type. This suggests that experienced pilots are better able to recognize specific types of SD than those with less flying experience. An alternative, though less likely, explanation would be that experienced pilots become disoriented more, perhaps as a result of taking more risks or flying more provocative maneuvers. If this were the case, one would expect to see a higher mishap rate among experienced pilots, but there does not appear to be a strong relationship between flying hours and SD incidents/mishaps[3-5,9,14,20]. The finding that age was positively associated with reports of display related SD (display-all and HUD related SD) is interesting and may indicate that older pilots have greater difficulty creating a mental model of where they are in space from primary flight reference symbology than young pilots.

Although, from this survey, pilots appear to be satisfied with the SD training they are receiving, previous SD surveys and mishap studies have not looked at the effects that type of training and satisfaction with training have on the incidence of SD in flight. In this survey, SD training using a variety of tools (lectures, ground-based devices and in-flight training) appeared to be better than didactic presentations alone, but only in-flight training had any significant positive relationship with pilots' experience of SD. This suggests that pilots who receive in-flight training are more likely to recognize, and be able to categorize, SD than their peers who have not had such training. However, the negative association between rating of training and some types of SD (visual, display-all and worst SD) is more difficult to explain if better training improves SD recognition. One possible explanation could be that good training prevents certain types of SD from occurring in the first place.

Although in-flight training appears to help pilots recognize SD, USAF undergraduate pilot training curriculum does not currently include standardized demonstrations of SD in-flight, though in-flight unusual attitude recovery training is given. Furthermore, with the exception of those fortunate enough to have experienced SD training in the Advanced Spatial Disorientation Demonstrator, pilots' experiences of ground-based training have been limited to basic demonstrations in the Barany chair or the aging Vista Vertigon This lack of availability of realistic ground training may explain the fact that ground training did not have a significant effect on pilots' recognition of SD in this survey. Alternatively, the fact that ~ 80% of all pilots surveyed had received SD lectures and ground-based demonstrations may have limited the ability to discriminate statistically between those that received or did not receive such training. Unfortunately, this survey was unable to identify whether advanced ground based SD demonstrators, such as the USAF's Advanced Spatial Disorientation Demonstrator, are more effective at teaching pilots to recognize SD than basic rotational devices.

This survey has shown that different aircraft streams produce different SD challenges for pilots to overcome. Not surprisingly, FJ and RW pilots tended to report more SD than did ME and TR pilots. These differences are a result of a wide variety of factors including G-loading, typical sortie altitude, balance of night versus day flying, use of visual aids (e.g., NVGs), etc. RW pilots operate in a unique motion environment quite unlike that of fixed-wing aircraft, so it is not surprising that the illusions experienced by RW pilots are different. With further analysis it would be possible to identify specific problem areas for individual aircraft types and, armed with this information, it should be possible to refine SD training to focus on issues pertinent to aircrew flying these aircraft.

As aircraft become more agile and greater sensory demands are placed on pilots (HMDs, greater use of night vision devices, etc.), the incidence and severity of SD are likely to increase unless more effective countermeasures are introduced. Better training would undoubtedly help, but is unlikely to be enough in and of itself. More effective orientational symbology, whether presented visually (e.g., on HMDs) or non-visually (e.g., tactile vest and 3-D audio), may also help pilots maintain spatial orientation and aid in recognizing and recovering from unusual attitudes should pilots become disoriented. Ground collision avoidance systems also have a role to play in reducing the incidence of controlled flight into terrain. The questionnaire used in this survey could allow researchers to evaluate the effectiveness of these countermeasures by providing them with a standardized tool for data collection and comparison.

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Preliminary Survey of Spatial Disorientation in UK Military Pilots and Navigators

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SUMMARY

Background: The direction of future spatial disorientation (SD) research and training is shaped primarily by the outcome of formal investigation of aircraft accidents and incidents. However, another source of vital information is aircrews' experience of SD that does not result in reported incidents. In order to access these experiences, Project Group 117 of Working Partly (WP) 61, Aircrew Standardisation Co-ordinating Committee (ASCC) developed a SD survey postal questionnaire (INFO PUB 61/117/5), with the aim of providing a standard format for data collection and analysis. This paper reports the findings of a preliminary survey of UK aircrew. ***Method:*** For the UK survey, a total of 1320 questionnaires were distributed to 5 Naval Air Squadrons, 22 Joint Helicopter Command Units and 7 Royal Air Force stations. Seven hundred and fifty-two questionnaires, comprising responses from 606 pilots and 146 navigators were returned. ***Results:*** Analysis was conducted primarily on the pilot data. The most frequently experienced SD episodes were the leans (by 92% of respondents), loss of horizon due to atmospheric conditions (82%), misleading altitude cues (79%), sloping horizon (75%) and SD arising from distraction (65%). When asked to rate the severity of their most recent SD episode, 3.5% (21) categorised their incident as severe ('flight safety was at risk'). In general, the frequency of SD episodes and ratings of severity of the worst ever SD episode were postively related to flying experience (hours-on-type, total hours $p < 0.05$). Overall, pilots who had received in-flight SD training reported more episodes of SD than those who had not participated in this training ($p < 0.05$). Differences in types of SD experienced were found between aircraft categories, which mainly reflected the use of aids to flying: more episodes of SD during NVG use were reported by rotary-wing pilots compared to fast jet aviators ($p < 0.05$). Fast-jet pilots reported more incidences of SD during HUD use than all other aviators ($p < 0.05$). ***Conclusion:*** This preliminary survey has shown that SD is still a significant hazard of military flying. The relatively high incidence of SD resulting from poor crew co-ordination and distraction highlights the need for situation awareness SD instruction in addition to the more traditional 'illusion' training. The differences in SD experienced between aircraft type suggests that specific airframe SD training may be required. This survey has also shown the role of experience (flying hours) in the recognition of SD, and has highlighted the potentially beneficial effects of in-flight SD demonstration and training. Overall, this study shows that the WP61 postal SD Questionnaire is a useful tool for assessing how SD training and experience may benefit the recognition of situations that may cause SD. However it is difficult to access those situations where aircrew were truly disorientated. Phrasing questions in such a way

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that differentiates between experiencing an illusion and being disorientated because of the illusion may be beneficial.

INTRODUCTION

Pilot spatial disorientation (SD) has long been identified as a major cause of UK military aircraft accidents. The percentage of UK accidents attributable to SD over the past 30 years has varied from 6% (Navy, 1972-1984; [1]), to 12% (RAF 1973-1991, [2]) and as high as 21% (Army 1971-1982, [3]). The most recent data show that pilot SD still contributes to UK military aircraft accidents. During a two-year period over 1999-2001, there were 7 accidents in the UK in which SD was believed to be a causal factor [4,5]. Four of these 7 mishaps resulted in fatalities of aircrew and loss of the aircraft.

Although most military aircrew receive some form of SD training (lectures and/or ground-based demonstrations, and/or in-flight demonstrations) the rate of aircraft accidents attributable to SD does not appear to be diminishing. For example, SD has been cited as a main causal factor in 4-5% of US military aircraft accidents (Army, Navy and Air Force) over the last 5 -10 years [6,7,8]. One reason for the lack of decline in this percentage, despite aircrew SD training, may be the introduction of new, agile aircraft (with unusual dynamic and visual environments), and an increase in frequency of night vision aided flights. Although they are undoubtedly a mission-enhancer, night vision devices (NVDs) provide the pilot with poor quality visual cues and are associated with a higher incidence of SD accidents relative to unaided daytime flying [9].

At present, the direction of future SD research and training is shaped primarily by the outcome of formal investigation of aircraft accidents and incidents. However, another source of information is aircrews' general experience of SD (that does not result in reported incidents). Infrequent SD surveys of aircrew over the past 50 years have reported some commonalty in aviator SD experience. The leans, and misinterpretation of aircraft orientation due to sloping cloudbanks or atmospheric conditions, were the most frequently reported SD phenomena in the majority of these surveys [10 as cited in 11;12,13]. Only the most recent surveys [12,13] have investigated SD experiences during visually aided flights (e.g. Night Vision Goggles) or SD resulting from the use of Helmet Mounted Displays (HMDs) or Head-up Displays (HUDs). Between 2 and 14% of aviators surveyed by Sipes and Lessard [13] reported SD arising from NVDs, HMDs or HUDs compared to 94% for the leans, and 79% for the black hole illusion. The relatively low usage of these types of NVDs and displays amongst those surveyed may explain this apparently low percentage.

Durnford [14] completed the most recent questionnaire survey of UK SD experiences amongst Army aviators in 1992. Unlike the previously cited surveys, which were concerned with the frequency and type of SD experienced, Durnford focused on descriptions and categorisation of the severity of SD episodes. The 440 respondents were asked to report the number of 'minor'('flight safety had not been jeopardised'), 'significant' ('flight safety had not been jeopardised, but could have been put at risk if circumstances had been different'), and 'severe' ('flight safety had been jeopardised') episodes both over their entire careers and the 4 months prior to the survey. Durnford found that episodes of the leans were generally minor. The most severe episodes of SD appeared to occur after inadvertent entry into instrument meteorological conditions (IMC). Ten percent reported that they had never been disorientated; 83% reported at least one minor episode; 56% had experienced at least one significant episode and 24% one severe episode over their entire careers. In the four months prior to the survey, the figures were 43%, 44%, 11% and 5% respectively.

Durnford found that younger pilots were more likely to have rated their worst ever episode as severe than older pilots. In addition, he reported that inexperienced pilots (in terms of total flying hours) were more likely to rate their worst ever SD episode over their entire career as 'significant'. Durnford also found that both Lynx helicopter crew members were disorientated in 44% of NVG related SD episodes.

Although all of the above surveys have provided information on SD incidence across different air platforms, services, and countries, inconsistencies between survey design and analysis has made it difficult to draw direct comparisons between airframe types and/or nations. In addition, the lack of a standard SD survey has made it difficult to track changes in SD incidence across time, or assess the impact of new aircraft or display technologies on pilot SD. To this end, Project Group 117 of Working Partly (WP) 61, Air Standardization

Co-ordinating Committee (ASCC) developed a SD postal survey questionnaire (INFO PUB 61/117/5) [14], with the aim of providing a standard format for data collection and analysis. This paper reports the findings of a preliminary survey of UK Navy, Army and RAF aircrew (undertaken during 2000), which used the WP 61 SD postal questionnaire.

SURVEY CONTENT AND DISTRIBUTION

The SD survey postal questionnaire comprises 2 sides of A4 and has been designed to ascertain the type and frequency of SD illusions experienced by aviators (in their current aircraft type) and a description of their most recent SD experience. The latter requires the participant to give details of his or her SD experience, indicate the conditions of flight at the time and rate the severity of the episode. Respondents are also asked to rate the worst ever SD episode in their current aircraft type. A copy of the questionnaire can be found in Annex A.

For the UK survey, a total of 1320 questionnaires were distributed to 5 Naval Air Squadrons (fixed-wing and rotary), 22 Joint Helicopter Command Units and 7 RAF stations (mainly fixed-wing) during September 2000. Seven hundred and fifty-two questionnaires, comprising responses from 606 pilots and 146 navigators, were returned by January 2001. The return rate of 58% is lower than the real return rate, as the number of questionnaires dispatched to each unit was overestimated. The questionnaire was well received by aircrew, which was mainly attributed to its concise nature. Data from navigators were collected in order to compare the frequency and type of SD experienced compared to pilots. Although SD in navigators should not normally adversely affect flight safety, there are some, abet rare, situations where pilots may call on their navigators to help re-orientate them when they are severely disorientated. Hence it was of interest to ascertain the frequency and severity of navigators' SD experience relative to their pilot colleagues.

UK DATA COLLATION AND ANALYSIS

The returned survey data were entered into a Microsoft Access® Database. The aircraft types were categorised as rotary, fast-jet, multi-engine or trainer. The descriptions of the most recent SD experience were categorised by Subject-Matter Experts (Pilot-Physicians) into the five main types of illusions (see Annex A): Body Sense, Visual, Miscellaneous, Displays, Other,. They also summarised the SD description into a few key words (e.g. 'the leans', 'hidden ridge during low level over snow-covered terrain', 'Pitch up sensation on acceleration after takeoff').

The analysis was performed to investigate the effects of the main independent variables: age, crew position, total hours flown, aircraft type, hours-on-type. Controlling for these factors, the effects of training type, rating of training and training personnel (medic, pilot-medic etc) on the dependent variables were also considered. The factors, factor type and levels used in the analysis are listed in Table 1 and Table 2. Due to the skewed distribution of the responses mainly towards 'never' and 'rarely', the responses were weighted as follows: 0 for 'never' and 1 for 'rarely or above'.

The dependent variables comprised the frequency of illusions, combined and in separate categories, and the rated severity of the most recent and worst ever SD experience (see Table 3). The display illusions were analysed as a group, with SD during NVG, HMD, HUD also analysed separately. It was decided to separate miscellaneous illusions (see Annex A) into three separate items: central psychological SD (giant hand, feeling of detachment), SD due to task saturation, and SD due to poor crew co-ordination, as these disparate items would provide meaningless data if analysed as a single group.

Table 1 Main independent variables used in the analysis

Variables	Type	Levels
Age	covariate	
Crew Position	factor	Student Pilot, Pilot, Instructor Pilot
Total Hours Flown	covariate	
Aircraft Type	factor	Trainer, Multiengine, Fast-jet, Rotary, Not Specified (NS)
Hours-on-type	covariate	

Table 2 Training independent variables used in the analysis

Variables		Type	Levels
Time since last SD training		factor	0-6, 6-12, 12-24, 24-48, 48+ months
Type of training:	In-flight	factor	Not Given, Given, NS
	Ground Demo	factor	Not Given, Given, NS
	Lecture	factor	Not Given, Given, NS
Rating of training		covariate	
Trained by		factor	Doctor, Physiologist, Pilot, Lecturer, Doctor &Physiologist, Doctor & Pilot, Other

Table 3 Dependent variables used in the analysis

Variables	Levels
All illusions	Principal Component
Visual illusions	Principal Component
Body Sense illusions	Principal Component
Displays illusions	Principal Component
Central psychological (giant hand & detachment)	No (never), Yes (rarely or above)
Distraction due to task saturation	No, Yes
Poor crew co-ordination	No, Yes
HUD illusions	No, Yes
HMD illusions	No, Yes
NVGs illusions	No, Yes
Severity of most recent SD experience	Never/minor=0, Significant=1, Severe=5
Severity of worst ever SD experience	Never/minor=0, Significant=1, Severe=5

The dependent variables 1-5 are the results of applying a principal component procedure to obtain a single measure to describe the effect.

The natural logarithm of total flying hours and hours-on-type terms was used in the analysis. The variables were selected from the possible combinations (age, crew position, total hours flown, aircraft type, hours-on-type, frequency of training, type of training and rating of training) by a ‘stepwise’ method. Responses with missing data were excluded from the each analysis on a case-by-case basis. Hence the total number of responses used varied for each analysis undertaken. Mutliple Analysis of Variance was used, with a significance criteria of $p < 0.05$. Newman-Keuls, Scheffe and Bonferroni post-hoc tests were performed to identify the source of any significant effects.

RESULTS FOR UK PILOT DATA

General descriptives – pilot data (excluding navigators)

Respondents included pilots from fast-jet (Tornado, Jaguar, Hawk, Harrier), rotary (Sea King, Puma, Lynx, Gazelle, Apache) multi-engine (mainly Canberra, Nimrod) and trainer aircraft (mainly the Squirrel helicopter). For 78 records, the respondents did not specify aircraft type, make and model, and it was not possible to confidently assume the aircraft type from the questionnaire origin or content. The mean age of respondents was 33.7 years (sd 6.7 years), with a range of 21 to 64 years of age. The mean number of total flying hours (over entire career) was 2,217 (sd 1,728 hrs), with a range of 40 to 12,300 hrs. The majority of the descriptive statistics are illustrated by Figures 1 to 5.

The most common SD experience was the leans (92% of respondents), followed by SD resulting from the loss of the horizon due to atmospheric conditions (82%). The rank order of the most commonly experienced SD is provided by Table 4.

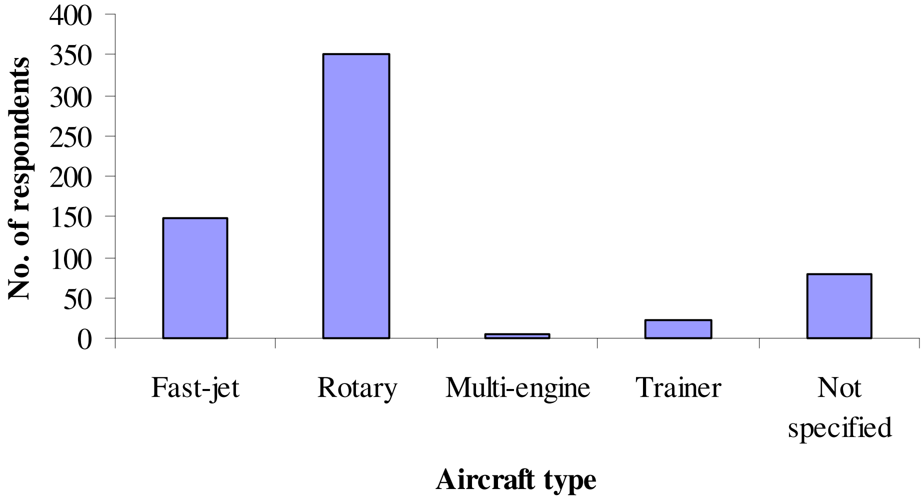

Figure 1 Distribution of responses by aircraft type

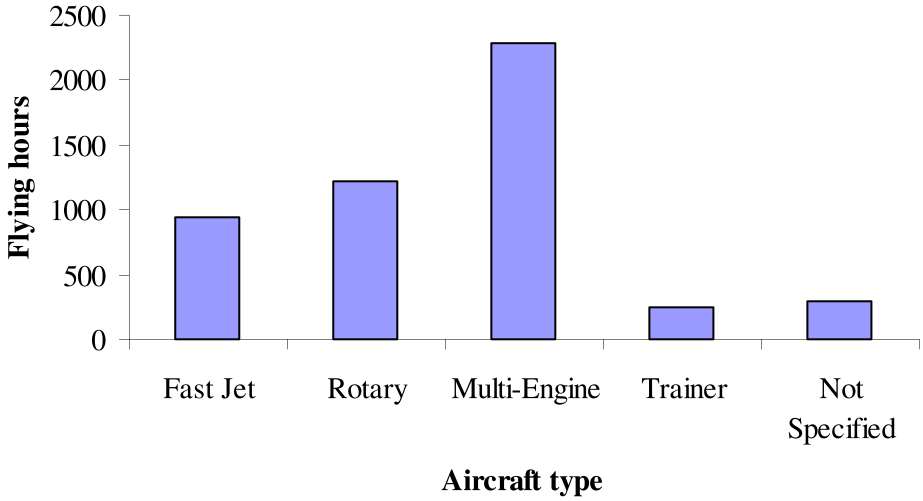

Figure 2 Mean flying hours by aircraft type

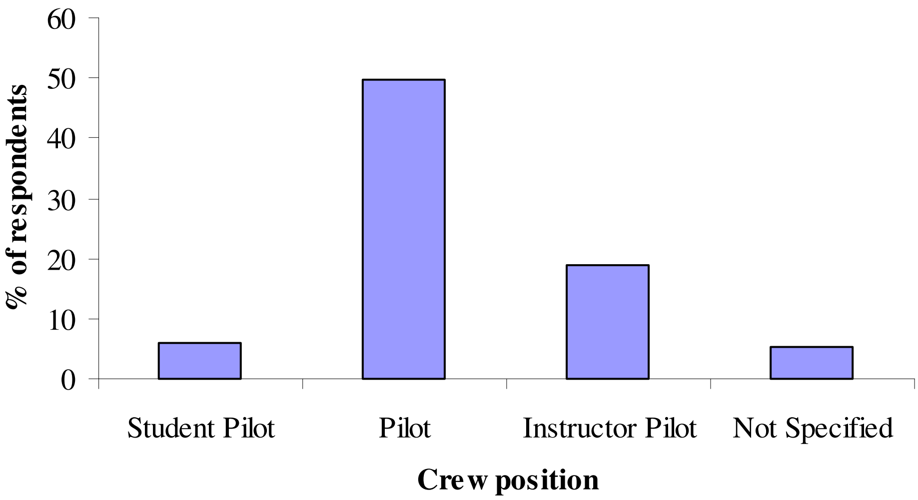

Figure 3 Distribution of crew position

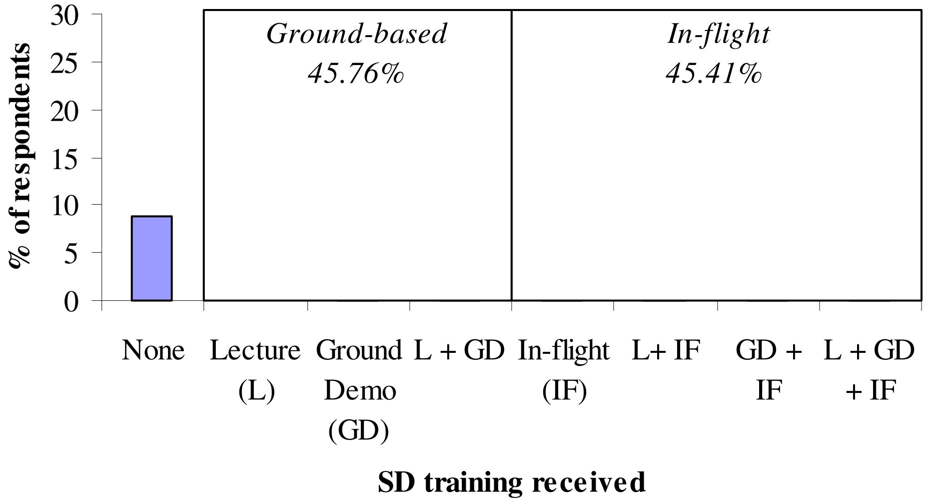

Figure 4 Distribution of SD training received amongst respondents. The mean time since last SD training was 3.5 months (sd 4.9 months) with a range of 0 to 45 months.

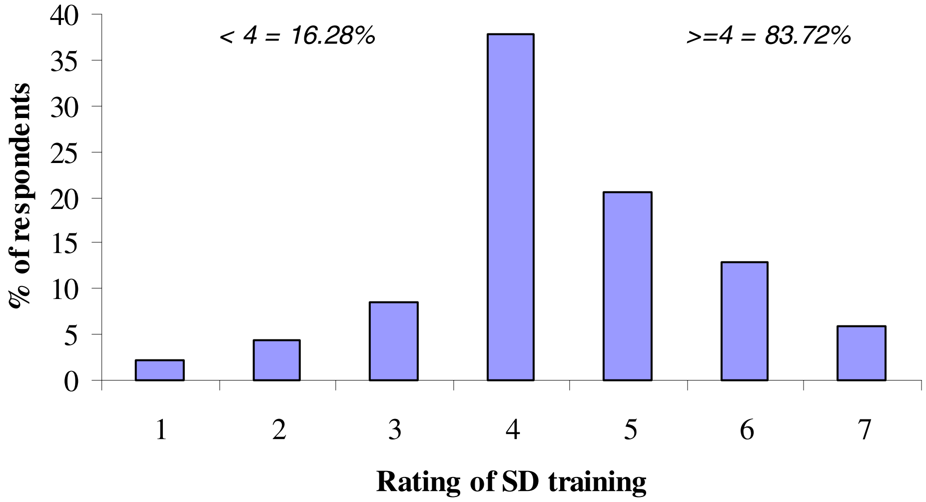

Figure 5 Respondents' rating of SD training (1 = no value, 4 = satisfactory, 7 = excellent)

The majority of respondents (78%) had either not experienced/recognised a recent episode of SD on their current aircraft type or had classified an episode as minor SD (flight safety was not at risk). However, 110 respondents (18%) reported a SD experience which they classified as 'significant: flight safety was not at risk, but could have been under different conditions'. Twenty-one respondents (4%) rated their most recent SD experience as 'Severe: flight safety was a risk'. Forty five percent of these severe incidents had occurred more than 1 year before the survey, with 30% at less than 1 year, 15% at less than 6 months and 10% at < 1 month. There were a higher number of responses (15%) in the 'severe' category of SD experience when the respondents were asked to rate their worst *ever* SD episode. These results are illustrated in Figure 6 and Figure 7. A selection of recent severe SD episode descriptions is provided below:

'Night fatigued (at work 18 hours, 8 hours flying). Alouette II helicopter, initiated climb to clear mountains next to sea. Intended to do a spiral climb but lost airspeed and started descending at 1500 ft.p.m. Recovered at 300 AGL (having lost 1000ft) by reference to instruments. Went home and cancelled the next sortie. No NVG.'

‘NVG approach at high elevation thought it was normal approach but we were going backwards and down. I was the Instructor Pilot at the time. I cross referenced with the instruments and recovered with forward cyclic. Pilot was very unsure what had occurred, and the sortie was terminated.’

‘Whilst flying in night the formation on a transit a turn was initiated. Our jet subsequently dropped back somewhat. Whilst trying to regain formation a millibar change was given and a descent was initiated. Whilst changing the HUD millibarsetting I looked up and saw the other A/C very close. At night I had incorrectly perceived the other A/Cs heading.’

‘Pulled up in IMC from the hover due to white out. Extreme difficulty in rolling out from turn. Solved by plugging in altitude hold and rolling wings level and letting aircraft fly itself.’

‘During night exercise with very little ambient, light and no horizon, I turned to cross the path of Sea King on reciprocal heading (over sea in company with ships). Estimated Sea King to be distant due to visual cues (navigation lights). As turn proceeded I realised that the Sea King was much closer than expected and executing avoided action. Estimated separation of 500 yds.’

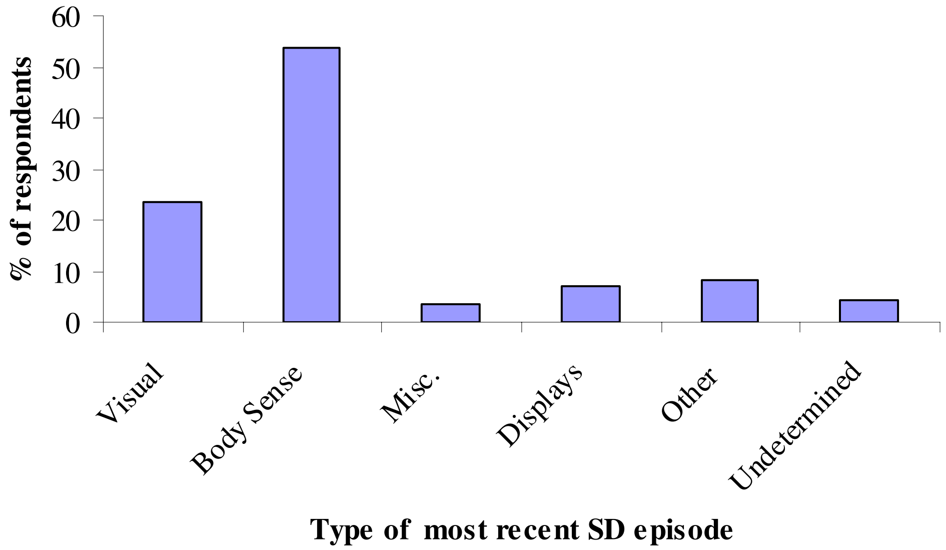

Figure 6 Distribution of type of most recent SD episode, as categorised by Subject-Matter Experts.

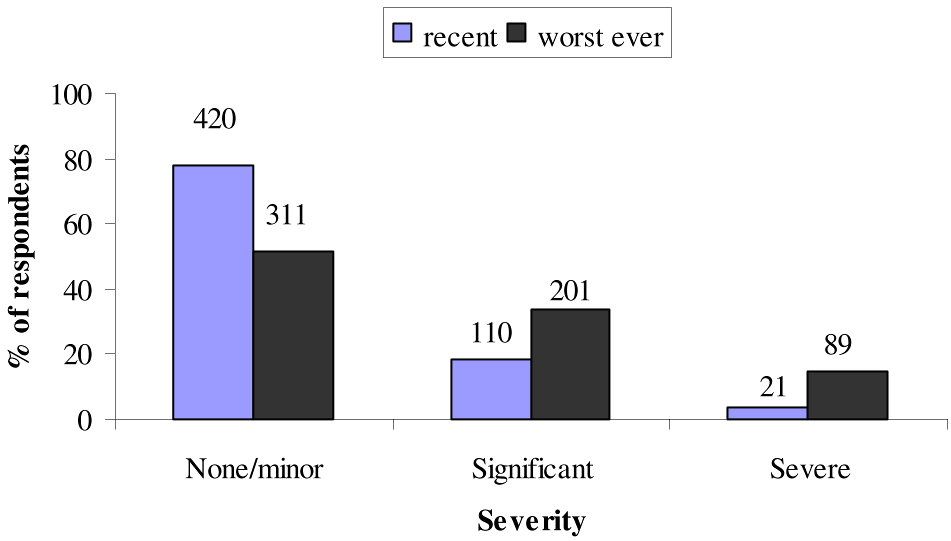

Figure 7 The distribution of respondents’ categorisation of their most recent and worst ever SD episode. The value displayed above the bars is the number of respondents in each category.

Table 4 Rank order of most frequently experienced illusions

Rank	SD experience	% of respondents
1	Leans	92
2	Loss of horizon due to atmospheric conditions	82
3	Misleading altitude cues	79
4	Sloping horizon	75
5=	Distraction	66
5=	Tumbling sensation (Coriolis)	66
7	Night approach	60
8	Loss of horizon due to sand/snow	56
9	Undetected drift (Rotary only)	55
10	Poor crew co-ordination	50
11	NVGs	48
12	Autokinesis	43
13	Graveyard spiral	43
14	Misjudgement of position	37
15	Elevator illusion	35
16	False sense of pitching up	34
17	G-excess	33
18	Giant hand	31
18=	Roll-reversal error	31
20	Head down displays	30
21	Inability to read instruments clearly following recovery from maneuver	29
22	False sense of pitching down	28
23	Instrument malfunction	24
24	False sense of yaw	20
25	False sense of inversion	18
26	Inappropriate use of sun, lights as vertical cue	17
27	Feeling of detachment (high altitude)	17
28	HUD	13
29	FLIR	11
30	SD whilst using drifting/descending aerial flare	10
31	Vertigo caused by flickering light	8
32	Graveyard spin	7
33	HMD	2

Statistical analysis

Table 5 provides an overview of the results from the statistical analysis of the UK SD survey data. As illustrated, it shows that factors that influenced the data were mainly aircraft type, crew position, hours-on-type, total hours flow, and whether pilots had received in-flight SD training.

All illusions

Analysis of all the SD illusions experienced by the respondents in their current aircraft type revealed an effect of aircraft type ($p < 0.0001$) and in-flight SD training ($p < 0.0001$). Fast-jet pilots reported more SD experiences overall than rotary and trainer aircraft aviators ($p < 0.05$). The respondents who had received in-flight SD training reported more SD experiences overall than those who had not received any in-flight training ($p < 0.05$). The linear covariate, hours-on-type, had a positive effect on all SD illusions ($p < 0.001$).

Visual

There was an effect of aircraft type ($p < 0.001$) crew position ($p < 0.05$) and in-flight training ($p < 0.001$) on experience of visual SD illusions. Pilots and instructor pilots reported more visual SD experiences than student pilots ($p < 0.001$). There were more visual SD illusions experienced by aviators who had received in-flight training compared to those who had not ($p < 0.001$). The covariate of total hours was found to have a positive effect on experience of visual SD illusions ($p < 0.001$).

Body sense

The experience of body sense illusions was affected by in-flight training ($p < 0.05$) and aircraft type ($p < 0.0001$). Pilots who had received in-flight training reported more body sense illusions than those who had not received in-flight training ($p < 0.05$). Fast-jet pilots reported more body sense illusions than rotary-wing aviators ($p < 0.001$). The linear covariate, hours-on-type, had a positive effect on body sense SD illusions ($p < 0.05$).

Display

Aircraft type had an effect on the experience of display SD illusions ($p < 0.001$). This was attributable to fewer reports of display illusions from rotary-wing pilots than fast-jet aviators ($p < 0.01$).

Central psychological

There was an effect of aircraft type on the experience of 'central psychological' SD illusions, giant hand and feeling of detachment ($p < 0.001$). Rotary pilots reported more of these types of SD experiences than trainer aircraft aviators ($p < 0.01$).

Distraction caused by task saturation

Spatial disorientation caused by distraction was affected by in-flight training ($p < 0.05$). Individuals who had received in-flight SD training reported more incidents of SD due to distraction than those pilots who had not received this training ($p < 0.05$).

SD caused by poor crew co-ordination

There was an effect of crew position ($p < 0.01$), in-flight training ($p < 0.01$), ground training ($p < 0.05$), and SD lecture ($p < 0.01$) on SD caused by poor crew co-ordination. Both instructor pilots and pilots reported more SD incidents of this type than student aviators ($p < 0.001$). Pilots who had received either in-flight, ground based training or an SD lecture reported more incidents of SD resulting from poor-crew co-ordination than aviators who had not received any of these training types ($p < 0.05$).

HUD

There was an effect of aircraft type on the experience of HUD illusions ($p < 0.0001$). There were more HUD illusions reported by fast-jet pilots than trainer and rotary aviators ($p < 0.01$, $p < 0.001$ respectively).

HMD

The covariate of total hours had a positive effect on HMD illusions ($p < 0.0001$), whilst hours-on-type had a negative effect on this data ($p < 0.0001$).

NVG

Aircraft type and in-flight SD training had an effect on the experience of NVG illusions ($p < 0.0001$; $p < 0.05$ respectively). Rotary-wing pilots reported more NVG SD experiences than fast-jet aviators ($p < 0.05$). Pilots who had received in-flight training reported more NVG illusions than those who had not received in-flight training ($p < 0.05$). The covariate of hours-on-type had a positive effect on the experience of NVG illusions ($p < 0.01$).

Severity of most recent and worst ever SD experiences

The severity of the most recent SD episode was affected by in-flight SD training ($p < 0.01$). Pilots who had received in-flight training reported more severe recent episodes of SD than those who had not received this training ($p < 0.01$). The covariate of hours-on-type had a positive effect the worst ever SD episode ($p < 0.001$).

Comparison of pilots and navigators

Data obtained from navigators was added to the responses obtained from pilots, and the principal component analysis for all responses in all categories ('All Illusions') was recalculated. Analysis of variance, including 'navigator' as an additional factor level in the category of 'crew position' was undertaken. This analysis found a significant effect of crew position ($p < 0.005$), which was attributable to fewer SD experiences reported by navigators relative to pilots ($p < 0.01$).

Table 5 Overview of results from statistical analysis of UK SD survey data (*p < 0.05, **p < 0.01, ***p < 0.001).

	Aircraft type	**Crew position**	**In-flight training**	**Total hours**	**Hours-on-type**
All	fast-jet > trainer* > rotary*		given > not given***		+ve ***
Visual		student < instr. Pilot*** < pilot***	given > not given***	+ve ***	
Body sense	fast-jet > rotary***		given > not given*		+ve *
Display	fast-jet > rotary**			+ve *	
Central Ψ	rotary > trainer**				
Distraction			given > not given*		
Crew co-ordination		student < instr. Pilot*** < pilot***	given > not given*		
HUD	fast-jet > rotary*** > trainer**				
HMD				+ve***	−ve***
NVG	rotary > fast-jet *		given > not given**		+ve**
Most recent SD			given > not given**		
Worst ever SD					+ve***

DISCUSSION

This preliminary SD questionnaire study is the first tri-service survey of UK military pilots and navigators, and the most recent in the UK since Durnford's (1992) survey of Army aviators [14]. The leans was the most commonly experienced SD episode, followed by SD caused by atmospheric conditions and misleading attitude cues, such as sloping cloud banks, an order in agreement with the previously cited SD incidence surveys [10, as cited in 11;12,13,14]. It is important to note that in all of these questionnaire surveys (including the current investigation) pilots reported SD episodes that they had *recognised* during flight and could categorise accordingly. It is therefore not surprising that the leans was the most frequently reported SD experience, as it is the most commonly stressed example of SD, and is a powerful illusion. Spatial disorientation experiences such as 'a false sense of pitching down with abrupt deceleration' may not be so recognisable or memorable.

Spatial disorientation due to the loss of situation awareness ('distraction due to task saturation') was reported by 66% of respondents, a figure similar to that reported by Sipes and Lessard [13]. Unlike the previous surveys, poor crew co-ordination was one of the main factors contributing to an SD event, having been encountered by 50% of respondents. The relatively high experience of both these types of SD episodes emphasises the importance of training aircrew to overcome and, most importantly, avoid the loss of situation awareness due to distraction and task loading. In addition, it highlights the need to train for good crew-co-ordination and investigate how poor crew co-ordination arises and its effect on SD. For example, are crews who have worked together for many months more or less likely to be disorientated due to poor co-ordination than those who have recently started to operate together? Research indicates that an increase in crew familiarity can foster complacency and over-confidence [16].

SD episodes during NVG use were experienced by a relatively high percentage (48%) of respondents. This is probably due to the 61% of rotary-wing pilots who participated in the survey. Pilots on this platform type are more likely to use NVGs than fast-jet aviators, which explains why more NVG SD experiences were reported by rotary than fast-jet pilots. Similarly, the greater experience of HUD SD illusions reported by fast-jet pilots relative to all other aviators is probably due to the more frequent use of HUDs in this airframe. Given these differences, it may be beneficial to provide specific SD training on SD resulting from NVGs to rotary pilots, and HUDs to fast-jet pilots.

The greater incidence of body sense SD illusions reported by fast-jet pilots compared to rotary-wing aviators is probably a reflection of the questionnaire design. The vast majority of the SD descriptions in this category could only be experienced in the fast-jet environment, with the exception of the leans and undetected aircraft drift, the latter of which was only completed by rotary-wing pilots (see Annex A). These facts may also explain why fast-jet pilots appeared to report more SD episodes overall ('all illusions') than other aircraft types.

The more experience a pilot had on their current aircraft type (hours-on-type), the more episodes of all types, body sense, and NVG illusions reported, and greater the severity of the worst ever SD experience. This data may simply reflect the greater chance of experiencing, and/or recognising, SD with increasing number of hours flown. The positive relationship between total flying hours and episodes of visual, display, and HMD SD episodes indicates that experience of these types of SD episodes 'carry over' to different aircraft types. For example, for fixed-wing aviators, visual illusions will be experienced during initial training in propeller aircraft, as well as during fast-jet training, whereas body-sense illusions will mainly be experienced in fast-jet aircraft. This serves not only to increase experience of visual SD over total hours flow, but also reinforces the recognition of types of visual SD. This may be reflected by the greater experience of visual illusions reported by pilots and instructor pilots compared to students. An interesting finding was the dichotomous relationship of total hours (positive) and hours-on-type (negative) with SD experiences related to HMD use. This suggests that as with visual SD, pilots will experience more episodes of HMD SD with increasing hours of flying experience. However, when pilots convert to a new type of HMD on a different aircraft, their experience may not readily transfer. This may be attributable to differences in sensor type (thermal or image intensifying; monocular, binocular or biocular), and symbology sets. Hence it is likely that pilots initially suffer SD episodes related to the new HMD, which reduce in frequency (and possibly severity) as they adapt to the technology.

One of the most interesting findings of the UK survey was the greater incidence of SD episodes reported by individuals who had received in-flight SD training. As previously stated, in completing this survey pilots reported SD episodes that they had recognised during flight and could categorise accordingly. It is possible that pilots who had received in-flight SD training were more able to recognise and categorise SD episodes for two reasons. Firstly, they may have experienced the types of SD that cannot be generated in ground-based simulators (e.g. pitch-up illusion, elevator illusion). In addition, in-flight SD demonstrations provide a realistic, contextual environment for SD training. The greater incidence of SD reported by those who received in-flight training provides evidence for the beneficial effects of this type of instruction. Once a pilot recognises that he/she is disorientated, they can take measures to rectify the situation (e.g. recovery manoeuvres).

Although all UK services provide their aircrew with in-flight training to prevent/overcome SD (e.g. procedures upon inadvertent entry to IMC and recovery from unusual attitudes) the Army Air Corps is the only service with a formal in-flight programme to demonstrate the limitations of the orientation senses [17]. An in-flight SD demonstration sortie has been designed for RAF fast-jet aircraft, although its implementation within the current training programme has yet to be established. It appears that RAF and Navy pilots receive 'informal' individual in-flight SD demonstration from some instructor pilots, although the nature, type, and frequency is currently unknown. It would be interesting to compare SD experiences and rating of demonstration and training between those pilots who have attended the formal AAC in-flight programme and those who have received informal in-flight RAF/Navy SD training. Regrettably, it was not possible to ascertain the source of pilots' SD training from the current data set. This could be achieved in a future survey.

Pilots who had received in-flight SD training rated their most recent episode of SD to be more severe than those who had not received this training. It is possible that these pilots may have responded to this question in terms of their rating of the severity of the SD itself as opposed to the effect on flight safety. A revision of this question to differentiate between severity of SD episode and effect of SD episode on flight safety may clarify this issue. The rating of 'severe' ('flight safety was at risk') was given by 89 respondents for their worst ever, and 21 participants for their most recent SD episode (the conditions of which have yet to be analysed). Very tentatively, these were 110 potential accidents. Given the beneficial effect of in-flight SD training on the recognition of SD, SD training should contain an element of in-flight instruction, and teaching specific to aircraft type (e.g. NVG for rotary). In addition, the relatively high incidence of SD related to poor crew co-ordination and distraction (task saturation) suggests that SD training should include these types of scenarios. We are currently undertaking a study evaluating the effectiveness of simulator training for this purpose.

The time since last SD training and rating of SD training appeared to have no effect on the frequency, type and severity of SD experienced. The latter may be explained by the high ratings given for the quality of SD training (over 80% of respondents rated satisfactory or above). The lack of any relationship between time since last SD training tentatively suggests that frequency of training may not be an issue affecting SD incidence. Overall, it appears that the most beneficial effect of training may not be the frequency, but the type of training provided (specifically in-flight).

Navigators reported fewer incidents of SD than their pilot colleagues. This is not a surprising result, as the navigator is not primarily responsible for the flying task. For example, navigators spend much of their time heads-in and may not experience the visual illusions.

Overall, while the results of the questionnaire provide interesting information on the recognition and classification of SD illusions in flight by aircrew, they do not give a clear indication of the frequency of spatial disorientation. It is difficult to discern from the results those instances that led to a significant error in aircraft attitude or position or that resulted in significant confusion in the mind of the pilot about the orientation of his aircraft. Such instances represent true spatial disorientation. By contrast, an illusion in flight can only be recognised if there is a simultaneous awareness of the true situation, through instruments or other visual cues (e.g. the leans), when it *might* therefore be argued that the pilot is no longer disorientated.

This questionnaire provides some evidence for the beneficial effects of SD training in the recognition of circumstances that could lead to spatial disorientation. In fact, the true instances of spatial disorientation may often be found embedded in the miscellaneous categories of distraction, poor crew co-ordination and errors in the interpretation of displays.

There were a relatively large number of missing data on aircraft type, make and model (13%). This may be attributable to the design of the questionnaire. It appears that this question is easy to miss (see Annex A). The layout of the questionnaire is currently in progress to rectify this problem.

CONCLUSIONS

This preliminary survey has shown that SD is still a significant hazard of military flying. The relatively high incidence of SD resulting from poor crew co-ordination and distraction highlights the need for situation awareness SD instruction in addition to the more traditional 'illusion' training. The differences in SD experienced between aircraft type suggests that specific airframe SD training may be required (e.g. NVG SD training to rotary-wing crews). This survey has also shown the role of experience (flying hours) in the recognition of SD, and has highlighted the potentially beneficial effects of in-flight SD demonstration and training in the recognition of SD. Overall, this study shows that the WP61 postal SD Questionnaire is a useful tool for assessing how SD training and experience may benefit the recognition of situations that may cause SD. However it is difficult to access those situations where aircrew were truly disorientated. Phrasing questions in such a way that differentiates between experiencing an illusion and being disorientated because of the illusion may be beneficial.

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ANNEX A - SPATIAL DISORIENTATION SURVEY

The purpose of this **anonymous survey** is to gather information from **aircrew** on the frequency and types of spatial disorientation (SD) being experienced in order to target future research and **help prevent SD accidents**. Please take the time to answer the questions as indicated, whether or not you have knowingly experienced SD in-flight. The definition of SD for the purposes of this survey is as follows:

An incorrect perception of your linear/angular position, or of your motion, relative to the Earth's surface or another aircraft, <u>SUFFICIENT TO AFFECT YOUR PERFORMANCE, SITUATIONAL AWARENESS OR WORKLOAD - HOWEVER SLIGHT THAT EFFECT MAY BE</u>.

Please complete **both sides** of this survey.

PART 1

Age (Yrs)	Crew Position *(Circle)*	Flying Hours (Total)
	Student Pilot / Pilot / Navigator/ Instructor Pilot	

What training have you received on SD? *(Circle all that apply)*	None / Lecture / Ground-Demonstration / In-Flight
How long ago did you last receive dedicated SD training?	______Years _____Months
Who gave you your last SD training (pilot, physiologist, etc)?	

How do you rate your overall SD training to date? ☐
Rating Scale (1-7): 1 (no value) to 4 (satisfactory) to 7 (excellent in all respects)

Please record how frequently you have experienced each of the listed SD illusions **IN YOUR CURRENT AIRCRAFT TYPE** with a mark in the appropriate column (if current on more than one type, choose the aircraft in which you have the greatest number of hours). **Please read each description carefully**. Do not include scheduled in-flight SD demonstrations.

Current Aircraft Type	Type / Model:		Hrs Flown on Type:	

Never = Never or N/A, Rarely = 1-2 episodes only, Seldom = <5% of **ALL** *sorties, Occasional. = 5-25% of* **ALL** *sorties, Freq. = >25% of* **ALL** *sorties*

N	R	S	O	F	DESCRIPTION	
					Inappropriate use of the sun, moon or northern lights as a vertical cue	VISUAL
					Sloping horizon – orientation against sloping clouds or terrain	
					Loss of horizon - SD caused by atmospheric conditions blending earth and sky	
					Loss of horizon - SD caused by blowing sand, dust or snow (brown-out/white-out)	
					SD while using a drifting/descending aerial flare as a reference	
					Misjudgment of position in night formation trail due to poor visual cues	
					Night approach to a runway with misleading visual cues – black-hole approach	
					Misleading altitude cues from ground texture (e.g., over flat water, small trees etc)	
					Apparent motion of a fixed point light source (autokinesis)	
					False sensation of yaw caused by anti-collision light reflecting off cloud/fog	
					Vertigo caused by flickering light – strobe light or sunlight through rotor disc/prop.	
					Inability to read instruments clearly following recovery from a flight maneuver	
					Sensation of rolling/pitching after abrupt head movement in a turn (Coriolis)	BODY SENSE
					False or exaggerated sense of bank in a high-G turn (G-excess)	
					False sense of upward/downward motion as if in an elevator	
					False sense of inversion – e.g., after abrupt level off	
					Recover from a spin, spin perceived in opposite direction, spin re-entered (graveyard spin)	
					Roll level from coordinated turn, sense roll in opposite direction, re-enter turn (graveyard spiral)	
					Leaning in response to a false sensation of bank after recovery to wings level (the "leans")	
					False sense of pitching up on take-off or when accelerating in flight	
					False sense of pitching down with abrupt deceleration in flight	
					Undetected drift/descent in the hover **(Rotary/VSTOL ac only)**	

Never = Never or N/A, Rarely = 1-2 episodes only, Seldom = <5% of **ALL** *sorties, Occasional. = 5-25% of* **ALL** *sorties, Freq. = >25% of* **ALL** *sorties*						
N	**R**	**S**	**O**	**F**	**DESCRIPTION**	
					Perceived inability to make input to correct bank angle (like a giant hand holding the wing down)	MISC
					Feeling of detachment/no longer being in control of own aircraft (high altitude/absent horizon)	
					SD caused by distraction or task saturation	
					Poor crew coordination	
					Problems interpreting spatial orientation information on the head-down displays	DISPLAYS
					Problems interpreting spatial orientation information on a head-up display (HUD)	
					Problems interpreting spatial orientation information on a helmet-mounted display (HMD)	
					Erroneous bank correction using any attitude indicator (roll-reversal error)	
					Disorientation while using night vision goggles (NVG)	
					Disorientation while using forward looking infra-red (FLIR) or other targeting aids	
					Disorientation due to instrument malfunction (proven malfunction only)	
-	-	-	-	-	Other disorienting illusions/factors *(please describe)*:	OTHER
					1.	
					2.	
					3.	

If you have experienced any of the above proceed to part 2

If not, please tick the box and return the survey. Thank you for your participation ☐

PART 2

How long ago did you **last** experience SD in flight? *(Circle one)* <1 Wk / <1 Mo / <6 Mo / < 1Yr / >1Yr

What was your last disorienting illusion/incident **in your current aircraft type**? *(Brief description - describe what you felt, what caused it, how you recovered – attach 2nd sheet if necessary)*

What were you doing at the time? *(Please circle appropriate condition)*

Take-off	Departure	Air-to-Ground	Air-to-Air	Air Refueling
Formation – Lead	Formation – Trail	Formation – Wing	Turning	Instrument Approach
Transition to Land	Low Level Nav.	Med/High Transit	Aerobatics	Hover
Other (Specify):				

Which of the following conditions applied at the time of this incident? *(Please circle as appropriate)*

Wx Conditions:	VMC	Borderline VMC	Intermittent IMC	IMC	Simulated IMC (Hood)		Not known
Illumination Level:	Bright	Overcast	Twilight	Dusk	Moon	Stars	No Moon	Not known
Devices (if applicable):	HUD	HMD	NVG	FLIR	Hood	Other:	Not known

Classification: Please indicate the severity of **this, most recent, (A)** SD incident and your **worst ever (B)** SD incident in your **current aircraft type**. *(one tick in each column)*

A	**B**	
☐	☐	MINOR – Flight safety not at risk
☐	☐	SIGNIFICANT – Flight safety not at risk but could have been jeopardized under different conditions
☐	☐	SEVERE – Flight safety **was** at risk

END OF SURVEY - Thank you for you help and participation

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A Spatial Disorientation Survey of Hellenic Air Force Pilots

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SUMMARY

Introduction: Spatial disorientation (SD) continues to be a largely unyielding problem in military and civilian aviation. SD training remains the sole solution of copying with this effect. In order to have more efficient training, we asked pilots the illusion they have probably had experienced in their flying career, attempting to study the prevalence and incidence rates of illusions and their correlation with specific types of aircraft

Method: An anonymous questionnaire was distributed to pilots of Hellenic Air Force during their annual physical examination at Hellenic Air Force Center of Aviation Medicine, between December 2000 and June 2001. The questionnaire gathered information such as age, type of aircraft flown, flying experience. The pilots were asked to give the number of times they experienced each of the listed illusions. Statistical analysis was performed by using SPSS 8.0

Results: A total of 407 surveys were collected. The mean age of the participants was 31.4±5.4 years old, and their flying experience 1012±908 hours. The most common types of aircraft flown were F4 and A7. 140 pilots (34.4%) answered that they had never experienced any kind of illusion. Among the other 267 pilots, 71 reported that they had experienced 1 illusion (26.6%), 185 (69.3%) had experienced 2-10 different types of illusions and 11 above 10 different types of illusions (4.11%). The top 5 illusions reported were the leans (47.2%) primarily with F4, the Coriolis illusion (39%) primarily with F4, blending of earth and sky (38,2%) primarily with F4 and A7, flight instrument reversal (24.3%) primarily with F4 and sloping clouds or terrain (22.8%) primarily with F16 and A7 . When asked to report their most personally critical illusion, 185 pilots responded. They classified the severity of their illusion to flight safety 111 (60%) as minor, 68 (36.75%) as significant and 6 (4,9%) as severe.

INTRODUCTION

Spatial disorientation (SD) continues to be a largely unyielding problem in military and civilian aviation. SD training remains the sole solution of copying with this effect. In order to have more efficient training, we asked pilots the illusion they have probably had experienced in their flying career, attempting to study the prevalence and incidence rates of illusions and their correlation with specific types of aircraft.

MATERIALS-METHODS

An anonymous questionnaire was distributed to pilots of Hellenic Air Force during their annual physical examination at Hellenic Air Force Center of Aviation Medicine, between December 2000 and June 2001. 407 pilots, all of which were men, served as participants. All of them were active-duty pilots.

A SD questionnaire was developed from a previous study (5). The questionnaire gathered information such as age, type of aircraft flown, flying experience. The pilots were asked to give the number of times they experienced each of the listed illusions. Each illusion was followed by a short definition. The pilots were also asked to report their most personally critical illusion. Statistical analysis was performed by using SPSS 8.0.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

RESULTS

A total of 407 surveys were collected.
The mean age of the participants was 31.4±5.4 years old, and their flying experience 1012±908 hours.
The most common current aircrafts flown were F4 and A7 (18,2% and 16,1% retrospectively).
140 pilots (34.4%) answered that they had never experienced any kind of illusion.
Among the other 267 pilots, 71 reported that they had experienced only 1 type of illusion (26.6%), 185 (69.3%) had experienced 2-10 different types of illusions and 11 above 10 different types of illusions (4.11%). The top 5 illusions reported were the leans (47.2%) primarily with F4, the Coriolis illusion (39%) primarily with F4, blending of earth and sky (38,2%) primarily with F4 and A7, flight instrument reversal (24.3%) primarily with F4 and sloping clouds or terrain (22.8%) primarily with F16 and A7.
When asked to report their most personally critical illusion, 185 pilots responded. The top 5 illusions reported were the leans (23.8 %) , the Coriolis illusion (12.97%), blending of earth and sky (11.9 %), sloping clouds or terrain (7.56%) and flight instrument reversal (7%).
When asked to classified the severity of their illusion to flight safety, 111 participants (60%) classified it as minor, 68 (36.75%) as significant and 6 (4,9%) as severe.
Almost all pilots reported that the tools that were used to recover from the illusion were their instruments.

DISCUSSION

The knowledge of the type of the most common experienced illusions and their correlation with specific type of aircraft flown or mission, will help having more realistic and effective training on which illusions to expect.

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Analysis of Spatial Disorientation Mishaps in the US Navy

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Summary

Spatial disorientation (SD) and subsequent loss of situation awareness (LSA) mishaps for military air forces, commercial aviation, and general aviation have an estimated annual cost in the billions of dollars. SD occurs when the pilot has an incorrect perception of the attitude, altitude, or motion of one's own aircraft relative to the earth or other significant objects. One example of the devastating effects of SD is the following mishap: A US Navy F-14 Tomcat, shortly after take off, crashed into a residential neighborhood destroying several homes and killing the two aircrew and three people on the ground. Causal factors in the mishap included SD and cockpit distraction. The Naval Aerospace Medical Research Laboratory (NAMRL) has developed an SD mishap analysis tool to support US Navy mishap boards in their investigations, to provide insight into the problem of SD in naval aviation, and to train aviators to avoid SD mishaps. The SD mishap analysis tool uses spatial orientation models and computer animation techniques to produce three-dimensional (3-D) computer simulations of SD mishaps.

Using mishap data from flight data recorders, eyewitness accounts, radar transcripts, and videotapes, an estimate of the mishap pilot's spatial orientation perception is calculated using spatial orientation models. These spatial orientation models are based on current literature and additional data from centrifuge, aircraft experiments, and aircraft mishaps gathered at NAMRL over the previous 40 years. The estimated perceived pilot orientation, along with computer models of the actual aircraft attitude and altitude, flight data, and actual pilot position, are then used to develop a 3-D computer simulation of the SD mishap under consideration. The current spatial orientation models used in the SD mishap analysis tool are adequate to address many types of mishaps, including mishaps due to the somatogravic illusion. However, the current spatial orientation models do not provide accurate results for some types of SD mishaps. Further research and development is required to enhance the mishap analysis tool to provide accurate descriptions of pilots' perceptions in the full range of US Navy aviation environments.

The SD mishap analysis system provides an intuitive tool that permits visualization of a complex problem. In the previous five years, results from these analyses have been used in mishap board reports, Judge Advocate General (JAG) investigations, congressional hearings, and television news reports.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

Introduction

Spatial disorientation (SD) and the subsequent loss of situation awareness account for a significant percentage of mishaps in aviation. As aircraft have become more reliable and safer from a mechanical perspective, the proportion of human-related mishaps has increased. Based on accident rates for the United States (US) Air Force, Navy, and Army, SD mishaps result in the loss of 40 lives on average per year (Gillingham, 1992; Matthews and Gregory, 1999; Braithwaite, Groh, and Alvarez, 1997). The cost of SD mishaps also includes mission failure, the impairment of mission effectiveness, and the monetary value of aircraft and equipment loss. Considering the number of military air forces, commercial and general aviation, the estimated annual material cost of SD mishaps is in the billions of dollars (Gillingham, 1992). In today's military aviation, there is an added emphasis on night flying, all weather capability, and low altitude missions which are all factors that increase spatial disorientation.

The safety of the aircraft and the ability to perform the aircraft's mission are highly dependent on the pilot having an accurate awareness of the current situation, including the state of one's own aircraft, mission goals, external conditions, other aircraft, and external hostile factors. The first and critical step in acquiring and maintaining situation awareness is to perceive the status, attributes, and dynamics of elements in the environment (Figure 1, shaded region, Endsley, 1995). In aviation, a pilot usually perceives elements such as aircraft attitude, altitude, or motion relative to the earth or other significant objects. SD occurs when the pilot has an incorrect perception of the attitude, altitude, or motion of one's own aircraft relative to the earth or other significant objects. This corresponds to an inaccurate perception of the elements in the current situation.

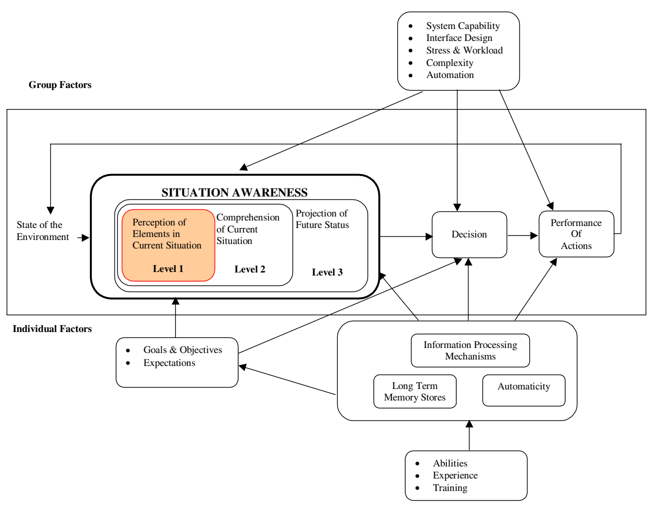


Figure 1: *Model of situation awareness (from Endsley, 1995).*

SD mishaps have occurred ever since the terrestrial human entered the dynamic 3-D aeronautical environment. As long as early aviators could maintain clear visual reference with respect to the ground or horizon, orientation did not pose a significant problem. However, "cloud flying" and other forms of flight in reduced visibility claimed many early aviators' lives (Ocker and Crane, 1932). The incidence of SD mishaps declined when pilots began to receive the appropriate training in the correct use of aircraft instruments, including the attitude indicator and the turn indicator (Stark, 1935). However, SD mishaps were not eliminated completely, because the attitude indicator is a visual instrument, and only provides orientation information when the aviator repeatedly looks at the instrument for sufficient time to see and cognitively process the information.

In our day-to-day terrestrial dynamic activities, spatial orientation is continuously maintained by accurate information from three independent, redundant, and concordant sensory systems; the visual system, the vestibular system, and the somatosensory system (skin, joint, and muscle sensors). These complementary and reliable sources of information are integrated in the central nervous system to maintain accurate spatial orientation awareness during static and ambulatory terrestrial conditions.

In the aeronautical environment, however, the vestibular and somatosensory systems no longer provide reliable information concerning the magnitude or direction of the gravity vector or "down" (Figure 2). During aircraft maneuvers, the almost continuous changes in aircraft acceleration expose aircrew to a resultant gravito-inertial force that is constantly changing in magnitude and direction. Under such circumstances, somatosensory and vestibular information concerning the direction of "down" will be inaccurate, and increased reliance must be placed on visual information if spatial orientation is to be maintained. Currently, the only reliable information is that obtained visually. Furthermore, the varying gravito-inertial force fields, misleading visual information and prolonged rotations can produce illusions of motion and position (see Benson, 1999 for a complete description of SD illusions). Thus the central nervous system, which on the ground normally integrates continuous accurate information from multiple sources, must now face the task of maintaining orientation and overcoming illusions by determining which sensory channels are presenting correct information and ignoring information from sensory channels that are not.

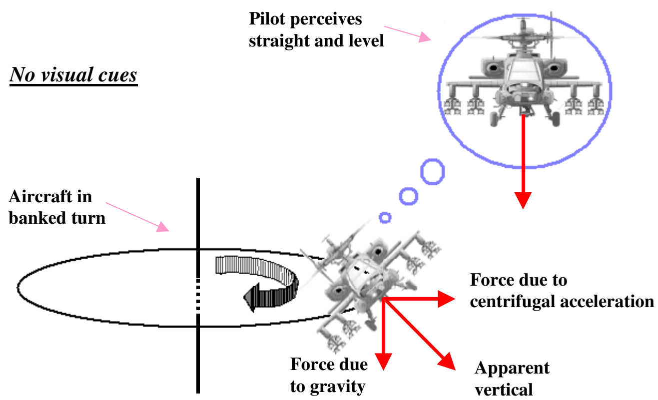


Figure 2: *Inaccurate perception of down (adapted from Benson, 1999b).*

Aviators are instructed to use a strategy of visual dominance, visual orientation cues are used to maintain spatial orientation to the exclusion of all other sensory cues, including vestibular and somatosensory (Gillingham and Previc, 1996). The pilot must learn to interpret the focal visual information on the attitude indicator and other flight instruments to develop a concept of where he is, what he is doing, and where he is going, and to refer to that concept when controlling his aircraft.

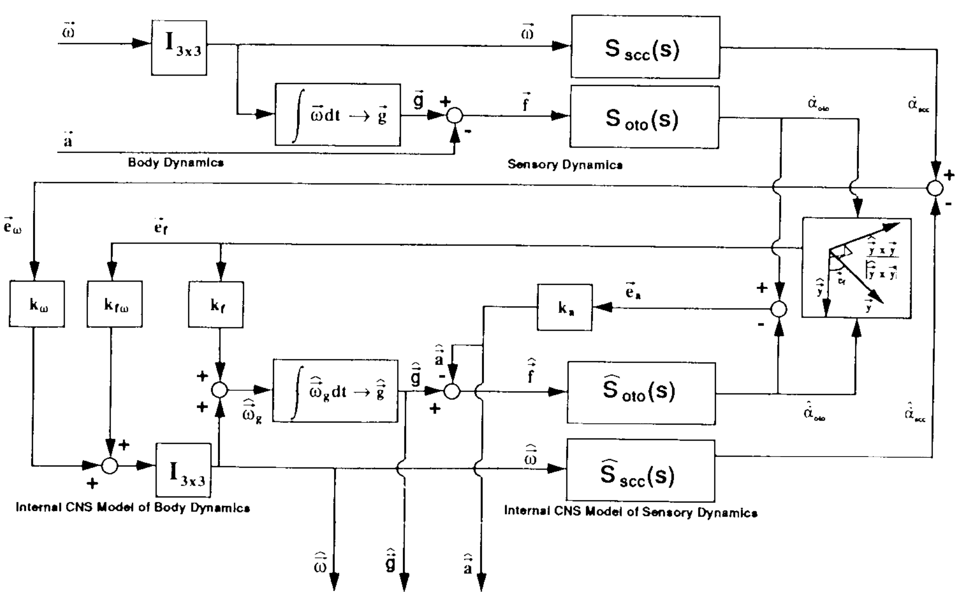
The typical SD mishap occurs when visual attention is directed away from the aircraft's orientation instruments and/or the horizon (due to, for example, temporary distraction, increased workload, cockpit emergencies, transitions between visual and meteorological conditions, reduced visibility, or boredom). Most SD mishaps are <u>not</u> due to radical maneuvers. When a pilot looks away from the horizon (loss of focal and peripheral visual cues), or looks away from his artificial horizon in instrument weather (loss of focal visual cues), the central nervous system computes spatial orientation with the remaining information at its disposal, vestibular and somatosensory. The vestibular and somatosensory information are concordant, but frequently incorrect. In such circumstances, it is physiologically <u>normal</u> to experience spatial disorientation. Furthermore, conflicts between focal visual and vestibular orientation information tend to resolve themselves in support of the vestibular information (Gillingham and Previc, 1996). This may lead the pilot to fail to make corrections to the aircraft's flight path, or to make inappropriate corrections, leading to an SD mishap.

Method

The Naval Aerospace Medical Research Laboratory (NAMRL) has developed an SD mishap analysis tool to support US Navy mishap boards in their investigations, to provide insight into the problem of SD in naval aviation, and to train aviators to avoid SD mishaps. The SD mishap analysis tool uses spatial orientation models and computer animation techniques to produce three-dimensional (3-D) computer simulations of SD mishaps.

Modelling of the spatial orientation system and predicting spatial orientation perception represent a classic bioengineering problem and there exists many examples in the vestibular sciences literature. Merfeld, Young, Oman and Shelhamer, (1993) reviewed the existing spatial orientation models and grouped them into two categories that are based on the underlying engineering formulation of the problem. The first is the "classical systems model" that uses classical control theory to model the components of the vestibular system. Information from these components is processed using regression analysis to estimate subjective orientation. Many authors have used this technique to describe components of the vestibular system, including Robinson (1977), Raphen, Matsuo, and Cohen (1977) for the semicircular canals and velocity storage mechanisms, and Grant and Best (1986) for the otolith organs. Mayne (1974) proposed a framework that explains how the information from the vestibular system is processed to give subjective orientation. This framework was the basis of a spatial orientation model implemented by Grissett (1993).

The second type of model is the "observer theory model" that uses optimal estimation theory to model spatial orientation first described by Oman (1980). Borah, Young, and Curry, (1988) and Pomelliot (1990) developed spatial orientation models based on this approach using Kalman filter techniques as the optimal estimator, and Merfeld *et al.* (1993) published a model based on observer theory that uses a constant gain estimator to predict spatial orientation (Figure 3). The SD mishap analysis tool uses both an observer theory model adapted from Merfeld *et al.* (1993), and a classical systems model adapted from Grissett (1993) to estimate spatial orientation perception.



The model outputs are estimates of angular velocity, gravity, and linear acceleration.

Figure 3: *Three-dimensional sensory conflict model (from Merfeld et al., 1993).*

There are currently 4 steps in the NAMRL SD mishap analysis process to develop a 3-D mishap simulation:

Step 1: Using data from flight data recorders; eyewitness accounts; videotapes; and ground, ship, and aircraft radar transcripts, estimates of the 3-D angular position and velocity, and 3-D linear acceleration of the mishap aircraft are calculated using the mathematical analysis software package, MatLab™ (The MathWorks, Inc.)

Step 2: The estimates of the 3-D angular position, angular velocity, and linear acceleration of the mishap aircraft are input into the spatial orientation models to produce an estimate of perceived pilot orientation. The SD mishap analysis tool uses both an observer theory model, and a classical systems model to estimate spatial orientation perception using the modelling analysis software package Simulink™ (The MathWorks, Inc.). Both of these spatial orientation models do not include visual or somatosensory inputs, and are based on vestibular models from current literature and additional data from centrifuge, aircraft experiments, and aircraft mishaps gathered at NAMRL over the previous 40 years. The spatial orientation models assume that the pilot is not using outside visual horizon cues, and the pilot does not look at the aircraft instruments.
`

Step 3: To determine the accuracy and validity of the perceived pilot orientation, including analyses when the model results are significantly different, the perception results are evaluated using data from other sources, including pilot control inputs, expert advice on the mission, and eyewitness accounts. If required, the estimated perceptual results are modified to overcome the limitations of the spatial orientation models to produce a more accurate estimation of the perceived pilot orientation. For example, in Figure 6, the perceived pitch at approximately 45secs was modified to account for the sudden stick position change. At that time, it was concluded that the pilot became aware of the "true" pitch, and performed the rapid movement on the stick.

Step 4: The estimated perceived pilot orientation, along with computer models of the actual aircraft, flight data, and actual pilot position, are then used to develop a 3-D computer simulation of the SD mishap under consideration using a 3-D software simulation package, Vega™ (MultiGen-Paradigm, Inc). This simulation package provides an intuitive tool that permits visualization of a complex problem. Aircraft models and databases are created in Creator™ (MultiGen-Paradigm, Inc) and also imported into Vega. The Vega mishap simulation includes models of the actual aircraft and flight data, actual pilot position, and estimated perceived pilot position as shown in Figure 4.

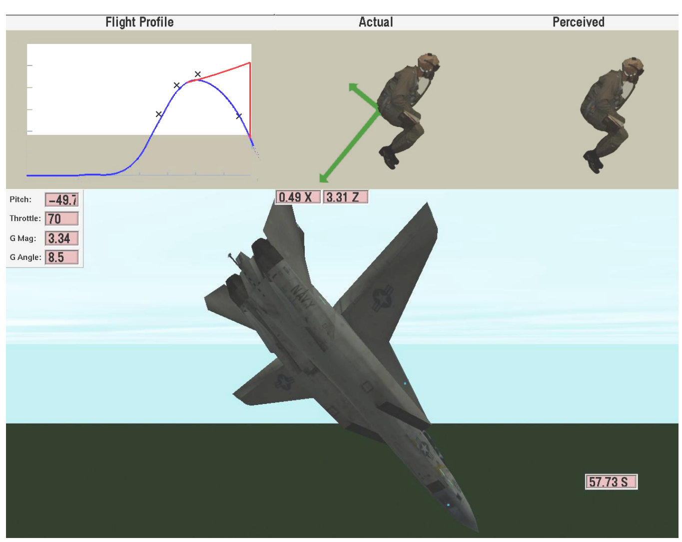


Figure 4: *Screen-shot of SD mishap tool 3-D computer simulation.*
Flight Profile is plot of altitude vs. ground track showing actual flight path (blue) and perceived path (red) based on predicted perception

These simulations provide an intuitive tool that permits visualization of a complex problem. Figure 5 shows a screen-shot from the analysis of an F-14 mishap from FY1996 to graphically illustrate the difference between the pilot's estimated perceived pitch (pitch up- calculated using the orientation models), and the actual pitch (pitch down – calculated from radar transcripts) that ultimately lead to an SD mishap.

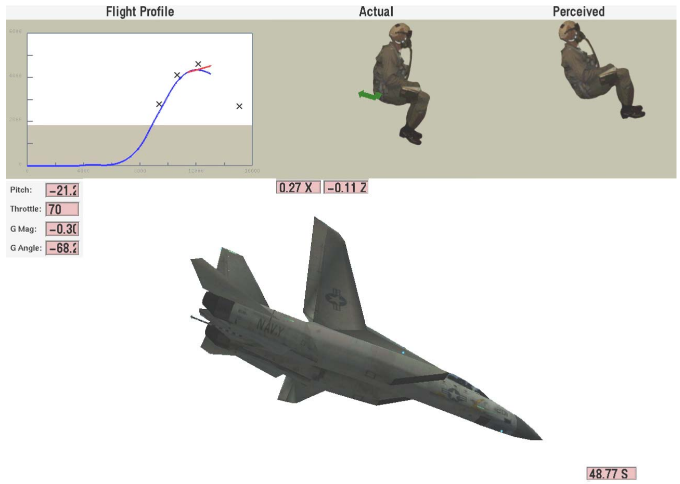


Figure 5: *Screen-shot of SD mishap tool showing difference between pilot perceived pitch and the actual pitch.*

Videos produced with the Vega simulation have been telecast on CNN, ABC News, and The Discovery Channel.

Results

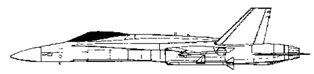
Table 1 shows the total mishaps for the US Navy for FY2001, and Table 2 shows the subset of these mishaps when the major causal factor was spatial disorientation. US Navy SD mishap statistics (26% of total mishaps, 50% of fatalities) for FY2001 are consistent with previous years and other services. SD mishaps remain a major problem in terms of lives lost (10) and aircraft (5). The analysis of an SD mishap from FY2001 that follows is provided to demonstrate the use of the SD mishap tool to support US Navy mishap boards in their investigations, and to provide insight into the problem of SD in Naval aviation.

Table 1: **US Navy Mishaps FY 2001**

F/A-18 Hornet	CRASHED DURING WTI TRAINING FLIGHT,	0
F/A-18 Hornet	NIGHT CATAPULT LAUNCH	**1 FATAL**
F/A-18 Hornet's	COLLIDED DURING NIGHT TRAINING EX.	0
S-3B Viking	CRASHED DURING DAY NATOPS CHECK FLIGHT	0
MV-22B Osprey	CRASHED DURING NIGHT TRAINING FLIGHT	**4 FATAL**
T-45A Goshawk	PORT MAINMOUNT EXTENDED DURING MACH RUN	0
TAV-8B Harrier	CRASHED ON DAY SHORT FINAL APPROACH	**2 FATAL**
T-45A Goshawk	CRASHED INTO WATER FROM DAY CQ PATTERN	**2 FATAL**
F/A-18 Hornet	SUFFERED MULTIPLE PELICAN STRIKES	0
F-14 Tomcat	LANDED GEAR-UP DURING NIGHT FCLP	0
T-34C TurboMentor	STRUCK WIRE DURING DAY LOW SAFE MISSION	**2 FATAL**
F/A-18 Hornet	CRASHED DURING DAY FERRY FLIGHT	**1 FATAL**
T-34C TurboMentor	CRASHED DURING DAY PROFICIENCY FLIGHT	**2 FATAL**
HH-46D SeaKnight-	CRASHED INTO WATER ON DAY TAKEOFF LHD	0
HH-1N	MADE HARD LANDING DURING CIVILIAN SAR MISSION	0
CH-46E SeaKnight	CRASHED INTO RIVER DURING DLQ ON NVG's	**3 FATAL**
F-14 Tomcat	FAILED TO RETURNFROM NIGHT MISSION	**2 FATAL**
F/A-18 Hornet	CRASHED DURING 2V2ACM TRAINING FLIGHT	**1 FATAL**
F/A-18 Hornet	RIGHT ENGINE FIRE ON TAKEOFF	0

Table 2: **US Navy SD Mishaps FY2001**

F/A-18 Hornet	NIGHT CATAPULT LAUNCH	**1 FATAL**
TAV-8B Harrier	CRASHED ON DAY SHORT FINAL APPROACH	**2 FATAL**
T-45A Goshawk	CRASHED INTO WATER FROM DAY CQ PATTERN	**2 FATAL**
CH-46E SeaKnight-	CRASHED INTO RIVER DURING DLQ ON NVG's	**3 FATAL**
F-14 Tomcat	FAILED TO RETURN FROM NIGHT MISSION	**2 FATAL**



F/A-18C HORNET
NIGHT CATAPULT LAUNCH

1 FATAL

Event Summary:

The Mishap Aircraft (MA) crashed into the water after night catapult launch. The Mishap Pilot (MP) was well rested and mentally prepared for the Mishap Flight (MF). MP spent significant time troubleshooting several discrepancies while on deck, all of which were satisfactorily resolved prior to MA launch. Weather conditions were overcast at 600-1000 ft, creating an extremely dark night under the low overcast. MP conducted a normal catapult shot with sufficient airspeed for flyaway. Almost immediately after launch, MP grabbed the stick and easily countered a slight roll to the right due to MA asymmetric condition. MP gradually applied forward stick during the climb out. After peaking in altitude at 224AGL, the MA responded to the forward stick by accelerating and following a nose down flight path toward the water. Just prior to water impact, MP realized he was in extremis and attempted to eject, but was already out of the ejection envelope resulting in an unsuccessful attempt. MP lost at sea.

Official Cause Factor:

AIRCREW: MP applied improper forward stick inputs during climb out due to the effects of somatogravic illusion.
WHO – Aircrew, Pilot at control, Pilot in command.
WHAT – Aircrew, Improper use of flight controls in the air, performed wrong action.
WHY – Physiological, mis-perception, vestibular illusion.

NAMRL Analysis:

Aircraft data from the flight data recorder that influences spatial orientation were analyzed and evaluated at NAMRL. There are several points of interest:

As you will note from the stick position plot (green stars, Figure 7) the pilot makes continuous small inputs/corrections until just prior to impact when he makes a large stick back input. This indicates he is conscious and aware throughout the 12 sec of flight (i.e., this was not a G-LOC mishap). It also strongly suggests that he became aware of his true attitude at the last instant before impact, when there was insufficient time for the aircraft to respond.

The plot of estimated perceived pitch (blue line with circles, Figure 7) is derived from the NAMRL perception model. It assumes that:

- On the night of the mishap it was a truly dark night and that there were no outside visual horizon cues.
- The pilot was not looking at the aircraft instruments.

This allows us to combine the resultant vector data of Figure 6 with the perceptual time constant decays from our model to produce the relatively constant perceived pitch up of 18 to 20 degrees from 4 sec after launch to just prior to impact. In a normal launch, the pitch up perception would decay more rapidly than indicated in this plot. However, the mishap aircraft is increasing in speed throughout the trajectory as the pilot pushes forward on the stick. This, in turn, increases the magnitude of the longitudinal acceleration vector and maintains the illusion of a pitch up perception. This is essentially a positive feedback situation for pitch perception. This false pitch perception can be classified as an example of the somatogravic illusion.

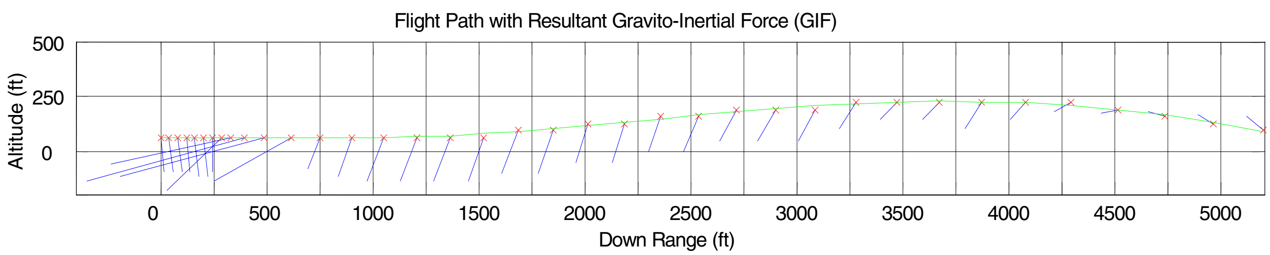


Figure 6: *Flight path with resultant Gravito-Inertial force*

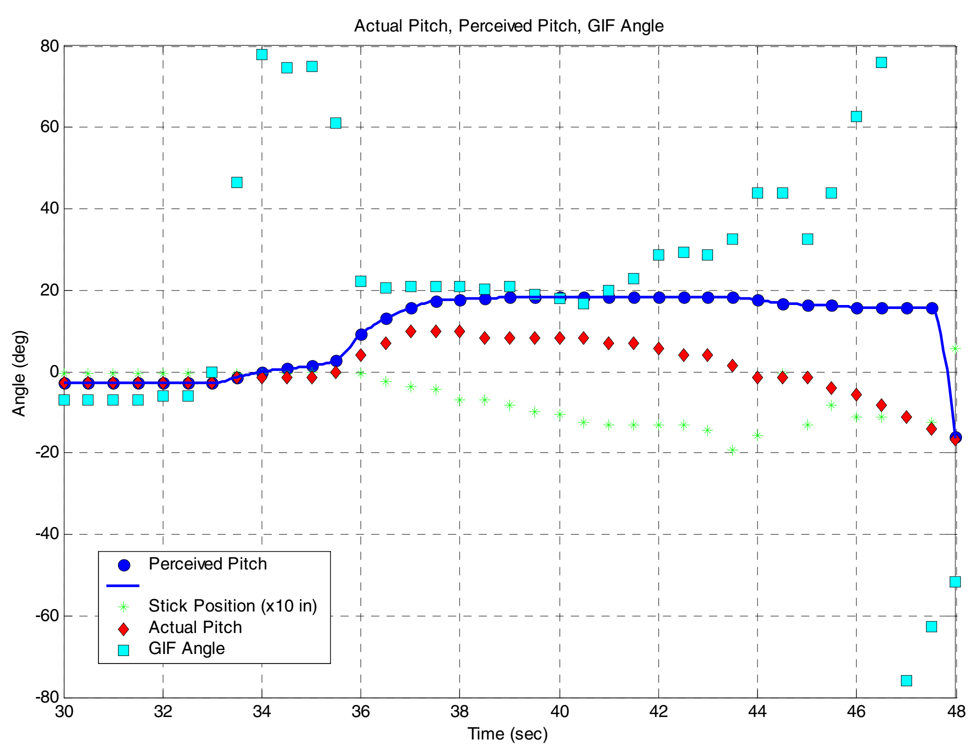


Figure 7: *Actual pitch, perceived pitch, Gravito-Inertial force angle*

As in all somatogravic illusion mishaps, it has to be assumed that the pilot was not engaged in a proper instrument crosscheck. The most frequent explanation is that an element of DISTRACTION or complacency occurred. It is difficult to believe that complacency could occur under the high stress conditions of a catapult launch at night. There was a "rash" of these mishaps in the 1960's leading to the research that has produced some of the data required to create the perceptual model. This mishap is almost identical to an S-3 launch mishap in FY1996 (Figure 8). The flight profile and duration match almost perfectly. In both situations no communication calls were received. Unfortunately, this F/A-18 mishap is a classic textbook example of the somatogravic illusion on launch.

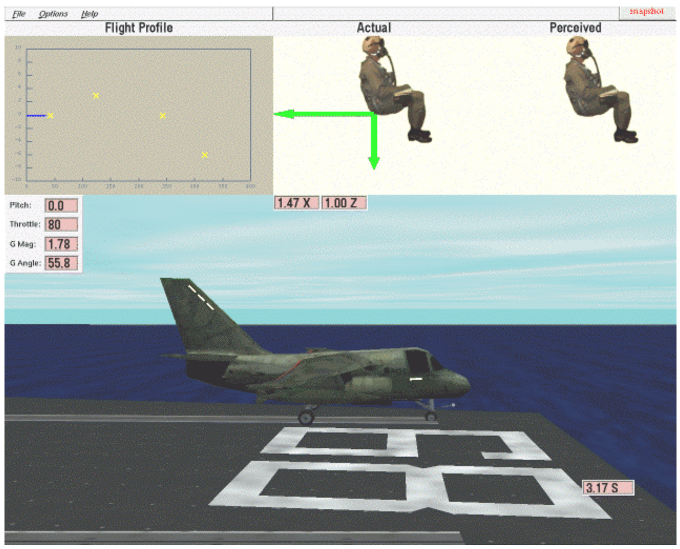


Figure 8: *Screen-shot from S-3 catapult launch mishap simulation.*

Discussion

Spatial disorientation (SD) mishaps for military air forces, commercial aviation, and general aviation have an estimated annual cost in the billions of dollars. The NAMRL developed SD mishap analysis tool uses two models of spatial orientation perception that are based on current literature and data from centrifuge studies, aircraft experiments, and aircraft mishaps gathered at NAMRL over the previous 40 years. The spatial orientation models currently used in the SD mishap analysis tool are adequate to address many types of mishaps, including the somatogravic illusion mishap illustrated here. However, these models do not address all of the relevant operational factors encountered in US Navy flight operations (e.g., flying with NVGs and flights with large roll maneuvers). Therefore, the current SD mishap analysis tool does not provide an accurate description of a pilots' perception in all US Navy aviation environments.

To enhance the existing SD mishap analysis tool, further research and development is required to produce an improved spatial orientation model. An ideal model would be a complete system containing mathematical representations of all sensory inputs (vestibular, visual, audio, tactile, proprioceptive), and an advanced mathematical representation of the central nervous system. Other improvements to the mishap analysis tool include adding intelligent, knowledge-based software to quantify the risk and extent of disorientation, and advanced computer animation techniques to improve the realism of the simulation. Intelligent knowledge-based software enables a computer to make a decision that is normally made by a human with special expertise. Such a software approach should provide more accurate, repeatable predictions of disorientation.

To extend the operating envelope of the spatial orientation model to all aviation environments, a combination of additional in-flight testing and laboratory testing is required. However, existing laboratory testing devices have limited degrees of freedom, and cannot fully reproduce the current and future aviation acceleration environment. Therefore, new laboratory multi-degree of freedom centrifuge systems need to be developed that are capable of providing data to improve models of spatial orientation.

The F/A-18 mishap presented in this report is <u>not</u> a rare type of mishap. For the past several years, NAMRL has assisted on at least one case per year of somatogravic illusion in the "fast mover" communities (three such mishaps in FY2001). Somatogravic illusion mishaps are not always associated with catapult launches, but may also occur in high performance takeoffs, landings and bombing runs over land. When it is a high visibility mishap such as the FY1996 F-14 mishap, where there were flagrant violations, it is all too easy to blame the pilot and ignore that the final link in the mishap chain was spatial disorientation. However, when the pilot is one of the best pilots in the squadron performing a routine mission such as a FY1997 F/A-18 mishap, then it is more difficult to reconcile as a mere lack of attention. Even the most dedicated, highly professional pilots are not immune to experiencing somatogravic and other vestibular illusions. These are *normal* physiological responses experienced by all pilots when they are subjected to acceleration forces in the absence of corrective visual inputs.

In this type of mishap, virtually every mishap board finds the pilot at fault for not maintaining an adequate "cross check" of instruments. There are often extenuating circumstances, such as operational demands or high workload. However, the bottom line is that the pilot simply did not maintain a sufficient crosscheck of the instruments and permitted the "aviate" portion of "aviate, navigate and communicate" to go by the wayside. As discussed by Wolfgang Langewiesche (1943), this complex talent must be developed through extensive training and maintained through practice; and it is the fragility of this concept that makes SD such a hazard. We continue to lose fine pilots and aircraft every year. Given that non-material solutions (e.g., training and safety stand-downs) have not reduced the SD mishap rate below the current level, the largest portion of the blame may now rest with aircraft designers, in particular human factors engineers, who design instruments that provide information only when the operator devotes visual attention to that instrument. There are a variety of technologies that may have prevented the SD mishaps cited in this paper, and more importantly future similar mishaps. It is the responsibility of mishap boards to make appropriate recommendations to the parties that can provide the necessary resources to effect changes in aircraft and information management systems.

Conclusion

The NAMRL developed SD mishap analysis tool permits visualizing causal factors in SD mishaps so that mishap boards, JAG investigations, and congressional hearings can conduct thorough and accurate investigations and make appropriate recommendations. These efforts will reduce SD mishaps in aviation and other high performance platforms.

Recommendations

1. Enhance the SD mishap analysis tool by:
    a. Conducting further research and development to produce an improved spatial orientation model that overcomes limitations of existing spatial orientation models.
    b. Develop intelligent, knowledge-based software to quantify the risk and extent of disorientation.
    c. Develop advanced computer animation techniques to improve the realism of the simulation.

2. Extend the operating envelope of the spatial orientation model through a combination of in-flight testing and laboratory testing. Develop new laboratory multi-degree of freedom centrifuge systems capable of providing data to extend the spatial orientation model.

3. All existing and future spatial orientation models need to be validated and compared against each other using both mishap and laboratory data.

4. The SD mishap analysis tool must be developed to operate in real-time, to allow for the eventual use of the analysis tool for real-time prediction in high performance platforms.

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Effects of Spatial Disorientation on Cognitive Functions

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Summary: Spatial Disorientation is well known by fliers but, generally it is too difficult to overcome. Even if it is managed, a pilot might still be at risk of serious dangers. After simulating Spatial Disorientation in laboratory conditions, any impairment of cognitive functions of the pilots was examined in order to find out whether Spatial Disorientation has any negative effect on cognitive functions. Two groups of, totally 82 pilot candidates who were to have Spatial Disorientation training in Turkish Aeromedical Center, were given WAIS-DSST (Wechler Adult's Intelligent Scale - Digit Symbol Substitution Test) or LCT (Letter Cancellation Test) to measure the differences of attention and percept after Spatial Disorientation. Both test results show that Spatial Disorientation causes impairment of cognitive functions.

Introduction: SD is a topic of interest, which has been discussed and investigated largely for years. Many articles have been written regarding the role of SD in mishaps. It has been shown that SD mishaps are the most fatal mishaps in military and commercial aviation.
Since this subject takes great importance lots of methods have been developed as a countermeasure and still a number of studies are being held to overcome this threat.
SD is defined as a subset of LSA, although some authors have offered new view and an operational definition for SD the majority supports traditional view. According to that, if a pilot is spatially disoriented then the one also lost situational awareness whereas a pilot can lose situational awareness without being disoriented.
In the light of above-mentioned definitions one can think when a disoriented pilot reestablishes his orientation then he can regain his situational awareness (in the lack of other LSA causes). But is this conclusion completely true? In other words Can SD have any postponed effect on SA or on cognitive functions even after establishing orientation
In our study we sought for any residual effects on pilots performance in cognitive tests after SD training.

Methods: The study was held in Turkish Aeromedical Center. Spatial Disorientation training Device "Gyrolab" was used. Gyrolab is an ETC (USA) made SD trainer offering both computer and manual controlled motion in four axis; yaw and roll (360^0), pitch (90^0 up and down), and planetary (up to $2.2G_z$ or 28RPM).
82 male pilot candidates at a mean age of 22.2 (22-24) were involved in the study. They had been sent to our center for initial physiological training at the beginning of Undergraduate Pilot Training. Before having the SD training they were given a lecture about SD and common illusions. Each pilot was given a pencil and a paper test at the end of the SD training, and a control test at rest period. Half of the trainees had their control tests two days before SD training and the other two days after training. Before having test each individual was shortly informed about the test.
Two pencil and paper tests were used: Letter Cancellation Test (LCT) and Wechler Adults Intelligent Scale Digit Symbol Substitution Test (DSST).
In LCT, there is one sheet of b, p, d, q letters (totally 546) in random order, subjects were asked to cancel all "b" s on their sheet as soon as possible in 120 seconds. At the end of the test correctly cancelled "b" s were counted as the test score.
In DSST there are 9 symbols as substitutes of 9 digits at the top of the sheet. The subjects were asked to substitute 100 digits, written in random order with the appropriate symbols as soon as possible in 120 seconds. At the end of the test correctly substituted digits were counted as the test score, same statistical analysis were made for both of the tests.

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Analysis were made regarding the whole group of subjects and with two subgroups according to the time of control tests before or after post SD training test distinctively, this was made to investigate the learning effect on test results.
The whole group's results were analysed using "Paired Samples Test" and subgroups were analysed using Wilcoxon test.
Mean test scores of the two subgroups were compared by using Mann Whitney U Test. The correlation between post SD test scores and control (rest time) test scores were analysed by using Pearson's correlation.

Results: In the DSST group of 40 subjects there is a decrease of 11.2 in the mean post SD test scores with respect to control (rest time) tests (89.7 versus 78.57). Test results are shown in Table I.
Either the whole group's or the subgroup's test analysis gave statistically significant results.

Table-I

DSST	Control		After SD		p
	Mean	sd	Mean	sd	
Total n=40	89,73	9,27	78,57	10,96	0,0001***
Grup 1 n=20	89,85	10,08	76,45	9,53	0,0001*
Grup 2 n=20	89,6	8,64	80,7	12,1	0,004*
P**	0.82		0.26		

**Wilcoxon test*
*** Comparison of two groups with Mann Whitney U test.*
**** Paired Samples t Test.*

The correlation between the rest time scores and post SD scores was not so strong (R:0.446) but, statistically significant (p:0.004) when analysed by using Pearson's correlation.

In the LCT group of 42 subjects, there is a decrease of 24.4 in the mean post SD scores with respect to control (rest time) tests. LCT test results are shown in Table II.
Either the whole group's or the subgroup's test analysis gave statistically significant results.

Table-II

LCT	Control		After SD		p
	Mean	sd	Mean	sd	
Total n=42	504.38	49.96	479.98	52.72	0,0001***
Grup 1 n=20	519.15	31.16	486.5	47.35	0.001*
Grup 2 n=22	490.95	59.98	474.04	57.62	0.008*
P**	0.38		0.43		

**Wilcoxon test*
*** Comparison of two groups with Mann Whitney U test.*
**** Paired Samples t Test.*

There was also a strong correlation between the rest time scores and post SD scores (R:0.793) and it was statistically significant when analysed with Pearson's correlation.

Discussion: SD is becoming a bigger problem day by day because technological advances in the high performance aircraft's new devices or new designs is going ahead of the advances in SD countermeasures. SD mishaps take great concern proportionally with the size of threat. Researches are made to avoid SD or SD related mishaps. And countermeasures are effective only in some extent. But SD is not the only threat for a pilot. Avoiding or overcoming SD is not the all case. The pilot should continue and complete flight duties. At this point he has to use his acquired skills, his knowledge, short and long term memory, information processing and all cognitive functions. Any impairment of these functions could also cause big threats, which we generally name as LSA.
As a definition SA is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future. This term comprises not only tactical arena, navigation, weather, communications, aircraft capability, but spatial orientation as well. It is clearly seen that SD will cause LSA at the same time but after orientation recovered there are still several task elements to be maintained in order to regain or maintain SA.

SD is a complex confliction causing the pilot to suspect the aircraft's flight parameters for some time. In this time it is possible that he can not completely concentrate on the flight, or the related task elements. In this case the problem would not be SD, but SA could be compromised in some extent.

In our study we aimed to see if there is any residual effect on cognitive functions after SD. For this goal SD was recreated in laboratory conditions then we used two simple tests.

Our test results suggest that under laboratory conditions, pilots had difficulty in managing the given simple tasks. They were more successful when they had the tests at rest time period.

Of course SD recreated in laboratory is not exactly the same with the real flight conditions. Therefore we don't know the exact effects occurring in flight. On the other hand, the tests that we used were simple and easy to apply but the results showed some training effect.

The time needed to totally recover from adverse residual effects of SD, the role of some individual factors such as flight hours, flight years, instrument flight or age and differences related with disorientation type was beyond the scope of this study.

In the future studies we are planning to use more standardised tests and to answer the above questions.

Conclusion: SD is always an important threat in aviation. But the problems we are usually dealing with might not be the whole iceberg. We also have to bring to light the negative effects after SD, the time needed to recover completely and useful countermeasures if possible.

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Pilot Disorientation, Sensorial Response Measured by Dynamic Posturography in SPAF Pilots

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INTRODUTION

Spatial disorientation (SD) is a real risk and one of the main causes of aircraft mishaps. Recent studies about accidents in military aviation (1,2,3,4,5) have calculated that approximately in 32% of the most serious accidents, SD is involved. Not in vain, practically the entirety of the pilots have experienced phenomenons of this type at during their flying career (6).

SD is a term used in aerospace medicine to describe a variety of circunstances occurring in flight in which the pilot fails to sense correctly the position, motion or attitude of the aircraft or of him/herself within the fixed coordinate system provided by the surface of the earth and the vertical gravitational (7).

The first person that demonstrated the existence of SD was the Major William Ocker in 1926, but in the last decades, the concept of SD has changed. SD should not be synonymous with vestibular or visual illusions alone, it also involves the behavioral responses and the cognitive integration of all sensory inputs (1).

To be able to guide ourselves in space, to maintain the posture and to make movements in a coordinated way, is a complex function that is organized starting from the information received by three sensorial systems, which are related to one another. The somatosensorial, visual and vestibular system (7).

During the flight the visual system provides the dominant information and it is the most important sense for the maintenance of the orientation and balance (8).

The vestibular system is an accelerometer capable of detecting movements of traslation, rotation and accelerations. It is related with the visual and somatosensorial systems by means of the vestibulo-ocular reflex (VOR) which stabilizes the eyes during the movement, the vestibulcollic reflex (VCR) which stabilizes the head and the vestibulospinal reflex (VSR) wich stabilizes the body (9).

Lastly, the somatosensorial system is formed by a group of muscles, tendons, articulations and nervous terminations of the skin. During the flight, the seated aviator perceives the forces that are exercised on him and he can describe many of the movements of the airplane for the pressure that the seat exercises on his body (10).

The SD takes place as consequence of a conflict among the received sensorial inputs (1,11,12,13).

A manifestation of SD is the motion sickness. Motion sickness is considered to be a normal physiological response to real or apparent motion to which an individual is not adapted (13). Its main symptoms and signs are pallor, cold sweating, nausea, which progress in severe cases to recurrent vomiting, and in less occasions, it is accompanied by headache, apathy and drowsiness (11).

This does not only happen in real flight, but it has been demonstrated that more than 29% of the subjects experience motion sickness after flights in spatial orientation / disorientation trainers (14), which, in order to provide more realism, have been developed vastly in therecent years (15).

The training in these trainers is gaining bigger relevance day after day, because they make the pilot experiences phenomenons of SD, teaching him to recognize them and to avoid them, to correct them or to counteract them later in real flights.

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It is interesting, therefore, the evaluation of the effects caused by this type of training on the equilibrium and coordination of the pilot and the influencerepercussion that it would have on his flight activity and on flight safety.

The clinical evaluation of balance is multiple, because it supposes the study of the somatosensorial, visual and vestibular systems. They are many exploratory techniques developed up to now, for the study of these systems, but only the Computerized Dynamic Posturography (CDP), marketed as Equitest by the signature Neurocom, it allows the integrated study of balance, differentiating the contribution of each one of the three previous systems in the maintenance of equilibrium.

Nashner began to develop it with funding by NASA, in 1970, to carry out his thesis, that was based on studying, with this new technique, the postural control of the students of the University of Massachusetts (16).

Later on, this method evolved and it was used to evaluate the postural control in astronauts returning from space (17) and for the clinical study of the alterations of balance (18) and it has even been proposed intended as an useful technique to predict the future susceptibility to the motion sickness (11).

The advantage of the CDP, regarding other tests, resides in that it can evaluate the interaction of the vestibular, visual and somatosensorial inputs of the subject on a independent way to determine the individual contribution of each one of the three sensorial informations, for the maintenance of balance (18,19).

Contrary to the other techniques, it allows to study the VSR in an independent way, through movements of the centre of pressure and projection of the centre of gravity of the body on a platform with motion (18), it also supplements other tests that study the OVR like the caloric tests and Barany´s seat (20).

However the CDP is not valid by itself to make a differential diagnosis among different vertiginous pathologies, but it is able to differ among normal and abnormal balance and it is a very useful method to quantify the functional state of balance in patients, so much in relation to their capacity to adapt to conflicting environmental sensorial stimuli, as to reorganize the sensorial inputs in the event of pathological deficiencies (18).

The objective of the present work has been to study the relationship between subjective sensations of spatial disorientation and modifications in the response of the visual, somatosensorial and vestibular patterns, by CDP, after exposing pilots, with flight experience, to diverse profiles of SD in the Gyro GPT II trainer.

The study hypothesis was that because of in the maneuvers of SD carried out with trainers, it produces movements that stimulate the visual, somatosensorial and vestibular systems, causing disorientation and motion sickness, it is possible to expect that these stimuli generate momentary changes in the organization and maintenance of balance and that those changes can be registered immediately by CDP after this stimulation.

MATERIAL AND METHODS

80 pilots of the Spanish Air Force participated in the study. It was carried out in the of Flight Physiology Unit and in the Otorhinolaryngology (ORL) department of the SPAF Aeromedical Center (CIMA) during the months from June to December of 2001.

The sample was selected at random among pilots that came to this Center to participated in the of physiological training programme. The inclusion criteria were to belong to the Spanish Air Force, to be in active and to develop flight duties as fighter or transport pilot.

In the first phase the pilots were subjected to diverse types of somatogyral illusions (coriolis, leans, spin) in the Gyro GPT II trainer. After that they answered a questionnaire including the following data: age, weight, height, habits (consumption of alcohol, tobacco), exercise, flight hours, type of aircraft flown, previous episodes of SD and motion sickness. Personal observations about the profiles trained and presence or not of symptoms of SD or motion sickness (nausea, vomiting, sickness, pallor) during the training were also collected in the questionnaire.

In the second phase the control of balance of these subjects was evaluated by dynamic posturografy in the ORL department.

The time between the first and the second phase should not excede more than seven minutes.

In order to avoid reducing the effectiveness of the test derived from learning effects, suggested by some authors (14), and because of theses subjects, for their professional activities, have been previously selected without any balance disorders or pathologies, we did´nt carry out a previous PDC in these pilots.

The CPD (Neurocom Equitest) is a computerized method developed for the study of the posture and balance whose system is formed by a mobile platform, a visual environment and a computer system. With the CPD, the sensory organization test of balance (SOT) and the motor control test (MTC) the responses of stretching and displacement and oscilllation of feet before small stimuli can be studied. We only carried out the SOT, beacause we consider that the MTC will not provide significant data in this study since motor responses are not affected in this type of simulators. These tests consist on valuing the subject's balance measuring his oscillation postural in anteroposterior position in six different sensorial conditions. In each one a different stimuli are applied annulling the visual and/or somatosensorial inputs to study the individual values of balance:

Condition 1: open eyes, fixed visual environment and fixed support platform.
Condition 2: closed eyes and fixed support platform.
Condition 3: open eyes, mobile visual environment and fixed support platform.
Condition 4: open eyes, fixed visual environment and mobile support platform.
Condition 5: closed eyes and mobile support platform.
Condition 6: open eyes, mobile visual environment and mobile support platform.

This method allows examine the ability of each person to use the somatosensorial visual or vestibular systems in the control of balance.

The results of these tests are evaluated automatically comparing them with the normal results and they are registered in a diagram of bars scoring the results from 1 to 100%.

For each one of the six conditions we consider as normal (control group) the mean values obtained in a study carried out in the ORL department in a population of 250 soldiers with ages between 20 and 45 without signs or symptoms of previous pathology of equilibrium (Table 1).

Table 1: Results of the equitest in a population of 250 soldiers (control group)

Condition	Means values N=250 Age = 20-45
1	94
2	92
3	91
4	82
5	69
6	67

For the sensorial analysis we consider as normal the mean values obtained in the same population for each one of the different patterns (somatosensorial, visual, vestibular and preferential) as it is showed in table 2.

Table 2; mean values obteined in the population taken as reference (control group) for each one sensorial pattern (somatosensorial, visual, vestibular and preferential)

SENSORIAL ANALYSIS	Means values N=250 Age = 20-45
Somatosensorial pattern Condition 2/ Condition 1	0.97
Visual pattern Condition 4/ Condition 1	0.87
Vestibular pattern Condition 5/ Condition 1	0.73
Preferencial pattern Condition 3 + 6 / Condition 2 + 5	0.98

The results of the equitest and the data obtained in the questionnaire were incorporated into a database using the Statistical Package for the Social Sciences (SPSS) 9.0 statistical computer program for Windows Release 6.0. We carry out a descriptive study of the variables using the Kolmogorov-Smirnov test to determine the adjustment to the normal of the quantitative variables. We calculate mean and standard deviation by the quantitative variables and proportions for the qualitative ones. For the comparison of means the Student´s t-test or ANOVA have been used according to the characteristics of the variables and the Chi2 test for the comparison of proportions. Chance probability of $p \leq 0.05$ was accepted as critical for statistical significance.

RESULTS

All subjets studied were male with ages ranging from 20 to 39. The mean age was 27.29 ± 4.74. The average height was 177.71 ± 7.52 cm (range from 154 to 195 cm) and the mean weight was 76.71 ± 9.58. 44.8% of the subjects were fighter pilots and 55.2% transport pilots. The mean flight hours was 1309.84 h.

The data collected in the questionnaire showed that 40% of pilots suffered from motion sickness, mostly during the instruction period and later starting again flight duties after a resting period.

According to the type of aircraft flown, we found that 43.3 % of fighter pilots and 33.3% of transport pilots described motion sickness symptoms but this difference not was statistically significant.

On the other hand, 50% of the pilots reported spatial disorientation episodes mostly flying under conditions of limited visibility and changing from visual to instrumental flight.

Relating to type of aircraft flown and presence of spatial disorientation episodes, were the fighter pilots who suffered these episodes with greater frecuency (73.3%), comparing them with transport pilots (25.9%), having besides this relation statistical significance ($p = 0.000 < 0.05$).

61.5% of pilots said to be experimenting light sensations with regards to the stimuli provoked during the training in the Gyro. These sensations were moderates in 34.6% of pilots, however in no case, major symptoms of motions sickness, like pallor, nausea or vomiting, appeared.

Table 3 shows the results obtained in each one of the six conditions of balance after subjected the pilots to trainning in the Gyro.

Table 3: Results of the equitest for each one of the 6 conditions of balance.

	N	Minimun	Maximun	Mean	Desv. típ.
CONDITION 1	80	86.00	98.00	94.78	2.25
CONDITION 2	80	80.33	97.00	93.12	2.55
CONDITION 3	80	87.00	97.66	93.10	2.52
CONDITION 4	80	74.33	96.33	88.55	3.94
CONDITION 5	80	5.00	94.33	68.65	11.70
CONDITION 6	80	.00	88.66	68.38	14.82

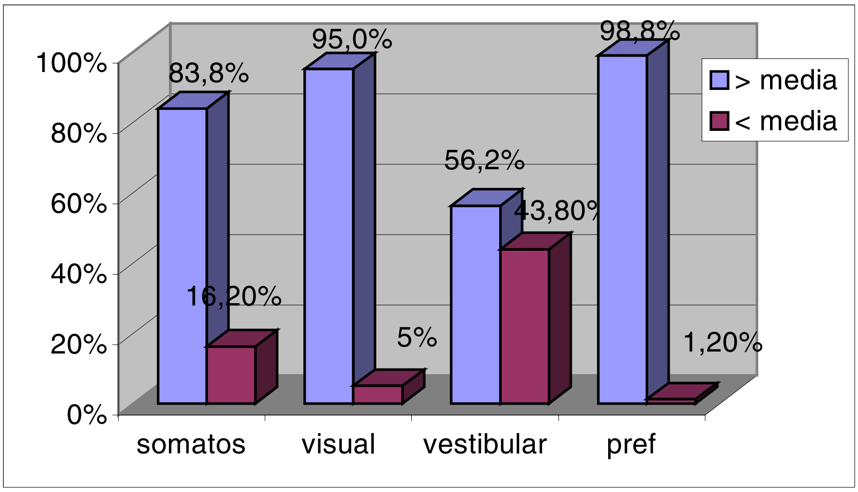
The results of sensorial analysis for visual, vestibular and somatosensorial patterns are in table 4

Table 4. Results of sensorial analysis

	N	Mean	Desv. típ.
somatosensoria	80	0.98	2.741E-02
visual	80	0.93	4.236E-02
vestibular	80	0.72	0.1240
preferential	80	162.49	12.5323
Total	80		

Comparing the results obtained after submmiting the pilots to several spatial disorientation profiles with the control group (fig. 1) we found that was the vestibular response the most affected, since the 43.8% of pilots reached values under the mean taken as reference (table 2) and even in three cases we found a disfunctional vestibular pattern. The 16.2% and the 5% of pilots presented a somatosensorial and visual pattern respectively, after stimulation, under the mean values comparing them with the control group. However the preferential pattern hardly was affected (1.2%) reaching a mean value above of control group.

Fig 1: Results obtained in pilots comparing them with control group



We did not find any relation statistically significant between the values obtained in the sensorial analysis for each one of patterns of equilibrium and age, height, weight and flight hours.

When we analysed type of aircraft flown and results of the equitest after stimulations we obtained a mean for the vestibular pattern lower in fighter pilots (0.67) comparing with vestibular values in transport pilots (0.73), being this relation statistically significant ($p = 0,01 < 0.05$).

On the other hand, there was not a statistically significance between results obtained in the equitest and sensations reported by the pilots during the training and collected in the survey.

However comparing each one of the differents patterns of balance with presence of previous symptoms of motion sickness we got a statistical significance for the vestibular pattern. That is, the majority of subjetcs with history of motion sickness showed higher values in the vestibular pattern after trainning in the Gyro, while the majority of pilots without previous symptoms of motion sickness the values reached for these pattern were much lower.

DISCUSSION

The DCP is a diagnostic technique that supplements other methods and it also provides new possibilities for the study of balance system. This method is used as much in pathological as in healthy people for the study of equilibrium, being able to determine the level of affectation of this system in those subjetcs exposed to certain movements and specific conditions, like astronauts returning from space, marines after a trip in ship and aviators after flights or simulator training (18,20,21).

All studies that have been carried out wiht this technique (11,13,14,19,20,22) have conclude that DCP is an useful test, because it offers the possibility to supress one or simultaneously two sensorial inputs, vestibular, visual or somatosensorial, that the subject receives for the organization and maintenance of balance, in order to evaluate the individual contribution of each one of these sensorial systems in the maintenance of equilibrium.

In our study, the results obtained by DCP have shown the functional state of balance in pilots after exercises of SD, in relation to their capacity to adapt to unusual or conflicting environmental sensorial stimuli, so it confirms that indeed changes in the functional organization of balance of pilots during the training have been produced, regarding the control group, and that this changes can be registered by DCP.

The ability to use the vestibular inputs was the more affected after trainning, showing in 43.8% of the pilots a vestibular pattern below the mean value of the control group and even in 3 cases a pattern of moderate dysfunction. On the other hand we observed in these pilots a higher dependence on the visual information for maintenance of balance and to overcome spatial disorientation phenomenons since practically the ability to use the somatosensorial and visual inputs were not affected, at the time that the preferential analysis, or dependence on the visual information for maintenance of equilibrium, was normal or lightly above the mean taken as reference.

This results indicates that the pilots, during the flight, use much more the information that they receive through the vision system than the one collected by the vestibular system and this could explain why the pilots describe more SD phenomenons in circumstances in wich the visual inputs are diminished like flying in bad conditions of visibility or changing from visual to instrumental flight. Other authors have also demonstred in their studies this increase of SD phenomenons in pilots flying under conditions of diminished visibility (23,24).

We coincide with Black et al. (17,20) who have demostred by DCP that astronauts after a space flight, presented a higher dependence on the visual and somatosensorial systems that the vestibular system for the organization and maintenance of balance, during the period of recovery after flight.

We have also found a relation statistically significant ($p < 0.05$) between previous episodes of motion sickness and values obtained in the vestibular pattern. That is, those pilots that have reported more motion sickness symptons during real flights, along their professional trajectory, presented a higher ability or dependence on the vestibular inputs for the maintenance of balance while the ones with no history of motion sickness gave a lower ability or dependence on the vestibular inputs for the manteinance of equilibrium.

These results also agree with Black (20) where astronauts with lower dependence on the vestibular inputs have manifested less symptoms of motion sickness.

On the other hand, we have not obtained a relation statistically significant between sensations manifested by the pilots during the trainnig and results obtained in the DCP.

In relation to the type of aircraft flown, the mean value for the vestibular pattern in fighter pilots (0.67) was lower that for the group of transport pilots (0.73), althought was not a correlation with motion sickness sensations described by the pilots after stimulation in the Gyro. So we think it could be the type of flight (higher accelerations and maneuverability in fighter aircraft), what determins the postural responses and the strategy of balance in the group of fighter pilots.

For this reason we think that the results obtained by DCP can be influenced by the type of individual training during long time and not for the stimuli generated during exercises of SD in the Gyro, and that they are the repeated expositions to complex movements and accelerations (higher in fighter than in transport aircrafts), the cause of changes in the strategy of balance in pilots (theory of the plasticity) (7,21), generating stimuli that alter or reduce the capacity to use the vestibular inputs for the maintenance of equilibrium, at least during a period of time and while the exposition to these stimuli is repeated in a regular way.

This indicates that the learning of pilots, to depend on the visual references above the vestibular ones, provides a higher resistance to disorientation episodes and decrease the presence of neurovegetatives symptoms associated to sickness. However, the high dependence or ability for the use of vestibular inputs, as use to happen after a resting or inactivity period, favors the appearance of sikness.

This habituation of the pilot to conditions of sensorial conflict, which occur in an adverse environmental like the air one, it has been showed in others studies (8,11,22).

However we cannot assert, as other authors (11,19) that the DCP is a valid test for the prediction to suffer motion sickness during flights, in inexperienced subjects, because our study has been carried out in personal with a great flight experience; although this technique could be useful to evaluate the level of training and adaptation of the pilot to the flight, according to its more or less dependence on the visual and vestibular inputs for the maintenance of balance.

CONCLUSIONS

We conclude saying that the results obtained by DCP have shown the functional state of balance in pilots after SD exercices, in relation to their capacity to adapt to unusual or conflicting environmental sensorial stimuli.

It was evidenced in pilots a higher dependence on the visual information for the maintenance of balance and to overcome spatial disorientation phenomenons and a lower ability or dependence on the vestibular inputs.

We think that the most dependence on the visual information above the vestibular inputs contributes to reduce the appearance of neurovegetative symptoms associated to sickness.

And lastly, the relationship between the results of the DCP and neurovegetative symptoms associated to sickness allows us to conclude that the DCP could provide information about the level of training of pilots and their sensibility to disorientation maneuvers.

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Motorists Vestibular Disorientation Syndrome Revisited

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Key words: automobiles, field dependency, rehabilitation, somatosensory system, spatial disorientation, vestibular system, vision, visual vertigo.

Abstract

We present a framework within which to understand the causes of chronic susceptibility to disorientation and how it may be resolved. Motorists Disorientation Syndrome is given as an example disorientation syndrome which may occur without sensory or marked psychological disorder and resembles pilots' disorientation. The syndrome may begin with an episode of disorientation or a sensory impairment and thereafter can cause dysfunctional behaviour. A neglected feature of disorientation is that contextual stimuli such as differential movements of parts of the visual field may support alternative interpretations affecting orientation. These are not necessarily at a conscious level but are still able to induce apprehension or inappropriate behaviour: a susceptibility to subliminal percepts. Once sensitised to the intrinsic ambiguities of a complex environment it becomes difficult to adjust gains and asymmetries or re-establish rules of reference between somaesthetic and vestibular signals. A fundamental problem in establishing rules for interpreting sensory input is circularity of reference between somatic and visual signals and vestibular signals of motion in space. Somatic and visual signals which give relativistic information about motion are referenced to vestibular signals of absolute motion in space for interpretation. Conversely vestibular signals are calibrated by reference to these other sensory input. Should a problem of interpretation arise in this potentially vicious circle the only recourse is to make an exploratory appraisal of the environment in which the natural first choice for perceptual sampling of world events is vision because of it teleceptive and panoramic power. Unfortunately, this tactic creates 'visual dependency' which, in a complex environment, risks creating increased susceptibility to vection illusions and visual vertigo (correspondingly, clinical experience indicates that the longer symptoms remain untreated the more patients suffer visual vertigo). Resolution of this deterioration is by recourse to cognitive behavioural therapy and desensitisation, commencing with dealing with simple stable environments and progressing through levels of increasing instability and ambiguity.

Introduction

Some 16 years ago Page and Gresty described a group of patients whose main presenting symptoms were of episodes of disorientation experienced whilst driving [1]. The incidents were generally of illusory veering or tilting motion of the vehicle which could be so compelling that the driver made corrective adjustments to the cars heading; often with untoward consequences. Some drivers affected in this way initially attributed the apparently abnormal motion of their vehicle to mechanical fault or extreme road camber and it was not until they recognised that the symptoms could occur under stable road conditions and in different cars that they sought help. At that time the experiences of disorientation were attributed to abnormalities of vestibular

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function and an attempt was made to explain the types of disorientation in terms of asymmetries of canalicular and otolithic function heightened by exposure to the conditions of motion experienced in a moving vehicle. This diagnosis was supported by abnormalities found on vestibulometry comprising asymmetries in nystagmus responses to rotational testing and caloric irrigation but it should be emphasised that these were slight. Since this original description the syndrome has been recognised widely and it has become clear that patients suffering motorists' disorientation (MDS) in general have few demonstrable vestibular disorders of significance. Consequently the syndrome has been classified as an extension of agoraphobia [2] or an aspect of a functional disorder which has been termed phobic postural vertigo [3,4].

Frequently patients affected in this way admit to other experiences of disorientation such as susceptibility to visual vertigo, but typical features of distinct vestibular disease in the form of an attack of vertigo are not present. Motion sickness susceptibility may be unremarkable in MDS and neither marked trait anxiety nor phobia are necessarily obvious contextual features. Accordingly, we view the syndrome as a functional spatial disorientation caused by heightened awareness of potentially disorienting stimuli (although, for obvious reasons, one which may provoke anxiety and phobia!). In this respect MDS has many features in common with susceptibility to disorientation which can occur in pilots. Our intention is to review the features of MDS, speculating on the specific mechanisms of disorientation as a springboard to proposing a framework which helps us to understand susceptibility to disorientation and rationalise its rehabilitation.

The clinical syndrome

Each year in the neuro-otological clinic with which one of the authors (MG) is associated an average of 10 patients out of 200 seen as outpatients present with primary MDS. Amongst patients with definite vestibular syndromes almost all are found to have problems with motion environments; in particular travelling as a passenger in a car, using the metro or buses and seeing motion such as streaming crowds of people. Typically the patients with MDS report very similar disorienting experiences on the road. These are described below together with an interpretation of how they may be generated. One should be aware that it may be difficult to unravel whether the description a patient gives of disorientation is of illusory movement or of a reflex countermeasure.

i) *The car feels as if it veers on wide open roads such as motorways*. This is by far the most frequent 'symptom' to be reported being a feature of every patient the writer has encountered. In a sense it is not unexpected since motorway driving may be monotonous and similar to a sensory deprivation situation, for example a pilot on a long flight at high altitude. My own interpretation of this illusion is that visual estimates of distance orientation and heading are impaired because of the paucity of nearby visual cues. It is interesting that drivers suffering illusory veering on motorways do not get the symptoms when driving in town. Although we have referred to the veering as illusory much may be real. The reader is probably aware of the 'lane drifting' often encountered on motorways both on the part of other drivers and of oneself. Hence illusory veering may be a heightened perception of true veering.

ii) *The car feels that is turning into vehicles being overtaking*. Everyone who drives will admit to some trepidation when overtaking, particularly at speed and when passing large vehicles such as buses and trucks. One is perhaps even more disquieted at oneself being overtaken by a large truck. A visual flow analysis of the situation (Figure 1) reveals one likely reason which is that the asymmetrical pattern of optic flow from ahead to the right versus ahead to the left is consistent with rotation which would take ones car into the path of the parallel vehicle. The disoriented driver appears to 'switch in' to this alternative interpretation of orientation.

Figure 1

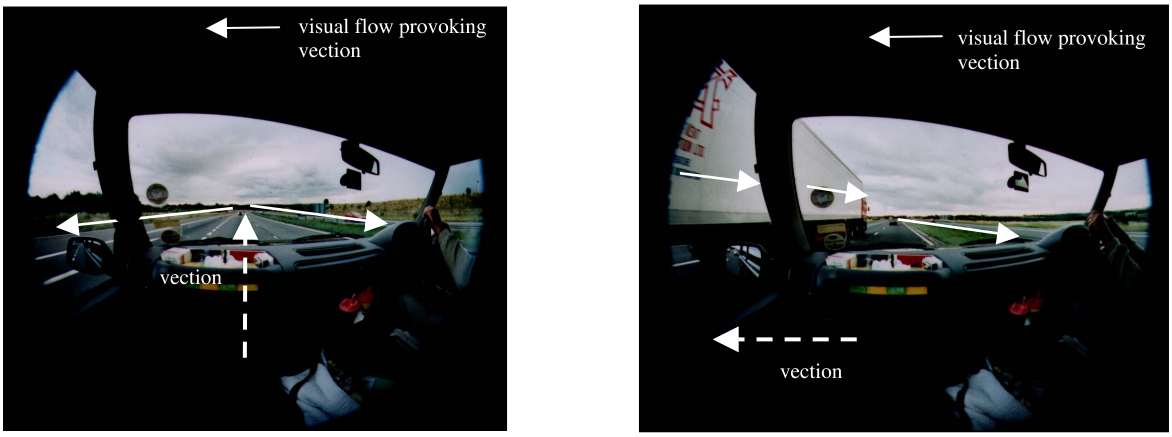

Figure 1 180° view taken with an equal-area fish-eye lens from the level of a drivers head in the cockpit of a car travelling on a motorway. The centrifugal visual flow when alone on the road is equivalent on the left and right sides confirming a straight ahead trajectory. A passing vehicle creates unequal flow which is consistent with a curved trajectory. The lens shows that the truck occupies almost one half of the are of moving visual field which is why the vection-illusion of turning can be so compelling.

iii) *The car feels that it is about to turn over when descending and rounding a bend* (Figure 2). Whilst descending the hill at constant velocity Ig is earth upright and the driver is tilted forwards of earth upright. Braking towards the bottom of the hill just before and into the bend will tilt Ig backwards with respect to g and the driver may perceive an enhanced forwards tilt (SOIg). When entering the bend on the flat the Ig vector rotates into the bend because of centripetal acceleration. The driver tilts from Ig upright out of the bend. In the disoriented driver the percept of tilt from inertial upright seems to dominate so that he perceives that he tilts from 'upright', firstly rotating forwards then backwards and sideways. At the same time the frame (ie, car seat) within which the body is 'anchored' by buttocks (the point of origin of the subject's Z vector) rotates in the opposite direction into the bend. In vestibular terms the tilt and rotation in different directions is a possible source of canal-otolith conflict [5]. This percept is similar to what one would experience if falling sideways and rotating at the same time, threatening a landing on ones back.

The key element in the situations we describe is that the force-motion environment is potentially ambiguous[6,7]. If the subject loses track of his cognitive appraisal of what is most likely to be happening or the most useful for behaviour then alternative interpretations of events spring to mind: the classic example being the railway train illusion wherein visual motion alone provokes the perception of self motion in the absence of contextual cues such as jolt and noise of ones own train moving. The cognitive context may also be inappropriate in that one may be far from the time of departure; particularly in the UK. Most readers will have experienced some instances of illusory motion or inappropriate apprehension provoked by motoring incidents. A common misperception is probably that one is drifting backwards after stopping in a line of slowly moving traffic which provokes a sudden stomp on the brake pedal.

Figure 2

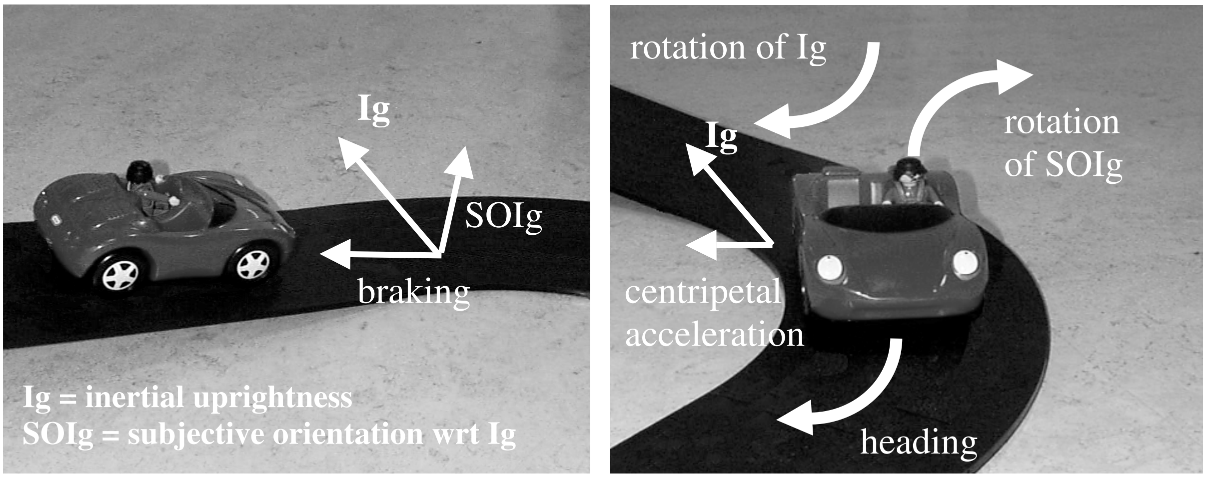

Figure 2 Changing orientation of driver with respect to 'inertial upright' during descent of a hill and braking into a corner. See explanation (iii) in text.

Two kinds of situations arise with subjects suffering MDS. Either they have become aware of illusory motion, which they accept as true, or they respond to an incident on the road which is inappropriate given the true configuration of what is happening. In the latter circumstance, the real situation may be consciously apparent to the driver but he still makes an inappropriate manoeuvre because of a pre-conscious percept. Some of the perceptions described above may occur at a pre-conscious level but may still provoke apprehension in normal drivers. Unconscious mechanisms have been shown for other behavioural modalities [8], for example being disturbed by a subliminal presentation of a word such as "cancer". Here we propose that a similar phenomenon may exist for ambiguous motion stimuli. We may consciously perceive one possible interpretation but others, held in reserve at an unconscious level, may also affect our behaviour.

MDS disorientation is difficult to rehabilitate. Furthermore approximately 30% of patients with proven vestibular disease are difficult to rehabilitate. A common feature is that the sufferer has been made over-aware of, overreacts to, or reacts inappropriately to quotidian instabilities of the environment such as moving crowds, traffic and using vehicles. Environmental motion makes them dizzy in the sense of feeling unstable and accompanying the dizziness is malaise with nausea which may be motion sickness. The malaise may include an element of headache. Psychological consequences may be anxiety, depression, panic and phobia.

Hypothesis: the mechanism of chronic susceptibility to spatial disorientation

A potent current theory of how orientation in space is organised proposes that somatosensory and visual signals of body movement are referenced to vestibular signals of orientation and movement of the head in space [9,10,11]. This is sensible, even necessary, in terms of the physical properties of the senses since vision and somatosensory inputs give relativistic information; on the basis of a visual signal of motion or somatosensory signals of force or changing position one cannot determine how much oneself or the external object or contact surface is moving. In contrast, vestibular signals render self motion in space. Given this parameter one can interpret other sensory input and apportion relative amounts of self and object motion.

In order to explain susceptibility to disorientation a further key factor should be considered; the vestibular system needs calibrating [12]. Its gain and phase settings are highly plastic at both the level of perception and reflex motor functions (see appendix for a detailed account of vestibular plasticity). The problem arises in that calibration is referenced back to visual and somatosensory input. This threatens circularity and all the problems of circular reference, including ambiguity and instability. Most features of a simple world without machines are stable so that the vestibular system maintains appropriate calibration. In a world involving vehicular transport the potential ambiguity of sensory cues to motion increases so that when a subject is disoriented he may find it difficult to establish stable features to which he can 'anchor' his perceptual estimates. Once this inherent ambiguity is recognised it is difficult for the sufferer to return to his naïve state of perceptual certainty, in part because instability is the true nature of the world and he finds himself in a state of chronic susceptibility to disorientation. Things are made worse if there is also a disorder such as a vestibular lesion because the subject finds greater difficulty in establishing a reliable frame of reference.

The key which unlocks the escape route from the vicissitudes of circular reference is the perception of what is stable and reliable in the world. This is attained through identifying reliable, invariant patterns in the consequences of our actions. This is classical 'Gibsonian ecological psychology' [13]. Unfortunately, before resolution of perceptual uncertainties is achieved a final pitfall threatens. Because of its teleceptive and panoramic attributes the obvious perceptual route to which we would tend naturally to have first recourse in any attempt cognitively to identify stable referents in the world is vision. Hence the patient who is challenged by some experience of disorientation tends to become visually dependent [15-18] and such tendency is probably enhanced if the observer was initially, already visual dependent [19] (eg susceptible to making errors of the visual vertical against a tilted frame or rolling background). The pitfall is that vision is arguably the most potent source of illusory motion; viz railway train illusions, waterfall illusions, parallax illusions, induced motion illusions, orientation illusions such as the "tilted" landscape seen from a tilting train [20]. Accordingly the visually dependent patient also begins to experience, and suffer from, visual vertigo. The patient originating idiosyncratically as a visually dependent subject is doubly jeopardised.

Reconciliation in therapy

Our 'model' for rehabilitation of disorientation assumes the following sequence of events.

i) An episode of disorientation or a sensory impairment causes dysfunctional behaviour in an intrinsically unstable ambiguous environment.
ii) The subject finds difficulty in re-establishing a working algorithm for interpreting sensory inputs (eg compensating gains and asymmetries; re-establishing rules of reference between somaesthetic and vestibular signals). This process is at an unconscious level but is manifest in consciousness as a feeling of disorientation or detachment.
iii) They recourse to a cognitive appraisal of world events: acting and perceiving consequences.
iv) The first choice of sensory input for evaluating the environment is vision which may be the worst choice in a complex environment because of visual relativism; eg causing vection illusions; visual vertigo. The longer symptoms remain untreated the more patients suffer visual vertigo.

The only resolution of the problems arising at stages (ii) and (iv) is cognitive reappraisal of environmental stability. Therapy should comprise cognitive behavioural therapy incorporating desensitisation to motion and commencing with simple stable structured environments.

Appendix

Evidence that vestibular system 'gains' are highly plastic and calibration is referenced to the other sensory inputs and cognition. Canal signals probably rely on vision and input from the neck for calibration [21,22]. The otoliths may use vision and multiple sources of somatosensory signals for reference. The calibration 'gain' and offset of otolith and canal signals may change quickly: eg, the gain of vestibular-ocular reflexes can adjust in seconds to spectacle corrections [23] or to contextual somatosensory input [24,25] and asymmetrical gains may be induced by manipulation of external visual motion [26]. Many normal subjects in the dark have offsets in the resting activity from their semi-circular canals [27,28]. Divers underwater who must rely on otolith signals to verticality become disoriented [29,30]. Vestibular 'perception' of self motion is highly plastic being subject to context, sensory input and mental set [31-37]. Finally, even vestibular 'reflex' gains are influenced markedly by cognitive 'set' [38,39].

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Disorientation, Dizziness and Postural Imbalance in Race Car Drivers, a Problem in G-Tolerance, Spatial Orientation or Both

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Abstract.
On April 28, 2001, Championship Auto Racing Teams (CART) drivers reported experiences of disorientation, dizziness, nausea and blurred vision during practice trials on the Texas Motor Speedway (TMS). Following the practice trials, there were reports of postural imbalance. As a result, the Firestone Firehawk 600 race scheduled for Sunday April 29 was cancelled,; the first time in auto racing history that concerns about driver intolerance to G forces caused a cancellation. The four drivers who did not experience problems had completed less than 20 laps (drive time of 8 min) whereas those reporting symptoms had driven on the track for more than 8 min.

Using track data (maximum average speed in qualifying laps, radius of turns, bank angle of turns), we have calculated the magnitudes of 'gravito-inertial forces" experienced by drivers on a number of speedways in the US. This reveals that drivers experience high G, particularly lateral G (Gy) on most speedways. Other tracks, eg., Dover Motor Speedway, also have steep banks and relatively small-radius turns, but have been raced at lower speeds. Some have banked turns that are steeper than the TMS turns. Calculated G-loads were greatest on the TMS, due to 220-250 mph car speeds. However, considering the semi- reclining posture of drivers, Gz on turns was not in a range that would be expected to produce G induced loss of consciousness (G LOC).

It is suggested that the pattern of visual, vestibular and proprioceptor stimulation contingent upon driver control actions during repetitive laps on the TMS is responsible for the dizziness, disorientation, blurred vision and nausea experienced by the drivers, and onset of adaptation to these conditions induced the post-exposure postural imbalance.

Calculation of tri-axial angular and linear accelerations during two imaginary laps on the TMS at speeds and lap times comparable to those reported are used to compare driver's stimulus conditions to conditions that produce spatial disorientation, nausea, and postural imbalance in centrifuge experiments, in military and commercial aviation and in other modes of modern transportation. Avenues of research necessary for advances in dealing with the problems of drivers, aviators, passengers in modern transportation and even 'dizzy' patients are discussed. A multi-national approach is necessary for near-term advances.

Background. On Friday, April 27, 2001, two drivers were unable to complete practice laps on he Texas Motor Speedway (TMS) due to disorientation, dizziness, nausea and blurred vision. Another driver reported being unable to walk away from his car for several minutes after practice laps on April 28. Later at a dinner meeting, 21 of the 25 drivers scheduled to start the Firestone Firehawk 600 on Sunday April 29 expressed concern about these symptoms. As a result, the race was cancelled; the first time in the auto-racing world that concerns about physiological tolerance caused a cancellation. Based on comments by the doctor for the Championship Auto Racing Team (CART), the media announced to the nation that the problem was G-induced Loss of Consciousness (G-LOC), a well known problem in Aerospace Medicine (7). The solution was for drivers to go through USAF pilot training on combating GLOC.

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Converging circumstances precipitated this historic cancellation. Beginning in 1998, improvements that were made to the track and to racing engines permitted higher sustained speeds. Advances in CART car engines and drive trains made these cars very fast; in fact CART cars may be the world's fastest team cars. Formula One cars have greater acceleration (0 to 100mph in 2 sec, compared to 0-100 in 4.2 sec for CART cars) but lower top speed. Figure 1 depicts TMS.

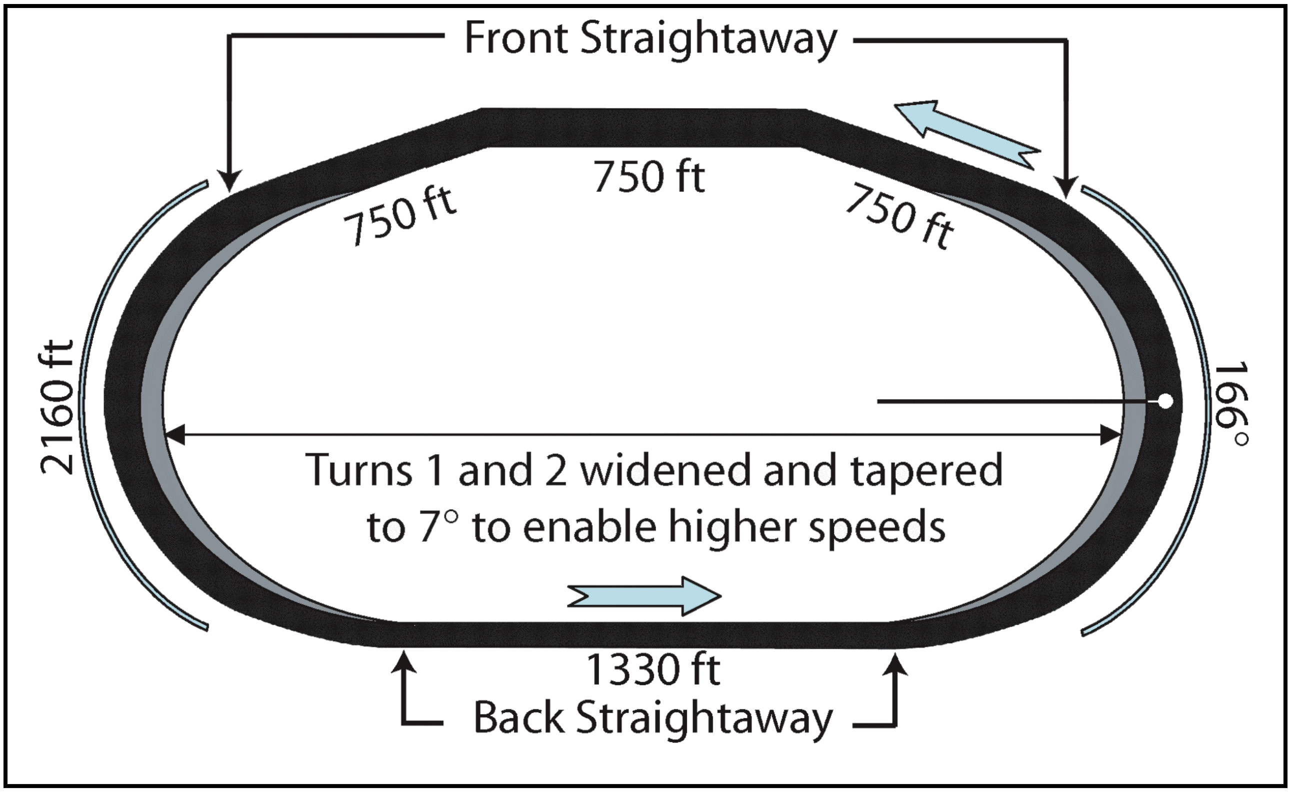

Figure 1. Sketch of Texas Motor Speedway (TMS) viewed from above. The Front 'Straightaway' is 2250ft (three 750 ft segments) in length, and the Back Straightaway is 1330 ft in length. The bank of Turn 1 and Turn 2 is 25deg., but, to enable higher speeds, Turns 1 and 2 were widened (near the infield) where the bank was decreased to 7deg..

At the time of the TMS problem, a paper by Gresty and colleagues (22) described passenger problems in Tilting Trains. Active suspension systems in trains operating in Switzerland, France and Germany permitted higher speed on curves. The active suspension system kept the Gravito-inertial Force (GIF) vector aligned with the 'upright' dimension of the coach, but the interior of the coach is the 'visual vertical' for passengers. Passengers viewing the passing countryside became Train Sick. Gravity sensors responding to the GIF were in conflict with the view of the countryside. Note that train tracks are banked very little; the turn radius of train tracks is sufficiently large to prevent high lateral G even at speeds of 150 km/hr.

Returning to the TMS, the banks on the turn at each end of the 1.5 mile oval are 24deg.. Because pilots routinely bank 60deg. in 2G turns to avoid slips and skids, GLOC seemed unlikely. However, we learned from a friend (Phil Babbcock) who restores classic cars and also participates in 'road' races, that drivers make controlled skids in cars which are especially designed to make high speed turns 'safely'. Internet sources (e.g., www.nascar.com, www.texasmotorspeedway.com) provided sufficient information, including lengths of straightaways (one of which includes two turns), turning radius (750 ft.) on the two 24deg. banked turns, and the top average lap speed (245.4mph) to estimate TMS G vectors. On the TMS 24deg. turns, 5G+ (lateral) would be experienced.

Early in 2001 in cool weather, an experienced driver tested the improved TMS, concluding that drivers would like the improved TMS, and that they should be able to drive full throttle around the 1.5 mile oval. However the average speed in test runs (224mph) was less than speeds on 27 April; the temperature was lower, and the number of consecutive laps in any one test run may have been less than 20.

On April 27, CART cars were completing laps in 22-25 seconds so that 20 laps were completed in about 8 minutes. Thus 21 drivers who completed 20 or more laps reported dizziness, and the 4 drivers who did not experience dizziness drove less than 8 minutes.

Was G-tolerance the problem? These very experienced drivers had never reported problems before. High G-loads are common in race cars. The structure, tires, suspension system and the semi-reclining posture of drivers are designed to obtain a low profile to prevent overturning during high lateral G. Speed reduction during full throttle during turns would result from the controlled skids (scrubbing) that experienced drivers often use in turns. Perhaps the media were right. Perhaps with a 24deg. bank, head-to-seat G is sufficient to produce occasional G-LOC. However, the head-to-seat component that threatens GLOC is much less as illustrated in Figure 2a.

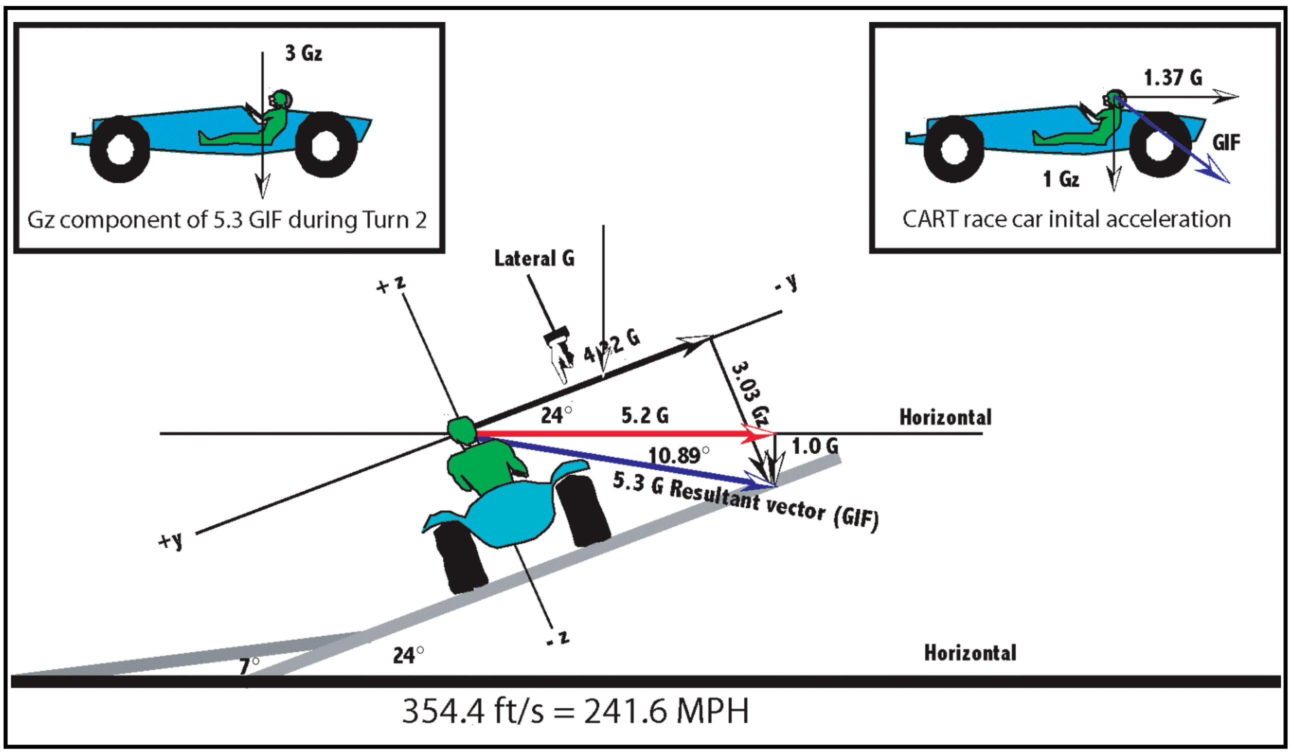

Figure 2a. At 240 mph (turn rate 27deg./s on a radius of 750ft), the driver's perceived centrifugal force is 5.2 G. The GIF components on the y- and z- axes of the head are 4.3Gy and 3.0Gz. If the driver steers high on the last segment of the front 'straightaway' and eases throttle while descending to the lower lane with 7deg. bank of Turn 1, the suspension system could level the driver's y-axis which would yield 1.0 Gz and 5.2Gy. While 'cutting the corner', the radius of turn may be increased to 800+ft which would reduce Gy. Considering the driver's posture (upper left panel), Gz=0.0 on the legs and less than 1.0G on the trunk. Upper right panel describes initial acceleration on the unbanked front straightaway.

Aviation Medicine and Race Car Drivers. In the 1940's and 50's, the US Air Force and US Navy conducted centrifuge studies to estimate how much G-tolerance could be improved by supine and prone pilot posture in high performance aircraft. Subjects were exposed to high Gx in supine and prone postures in centrifuge gondolas. Subjects exposed to 9+ Gx did not experience G-LOC, but there were after-effects. In Pensacola, a volunteer became dizzy shortly after exposure to 10Gx, and was bed-ridden for about two weeks due to dizziness and postural imbalance which persisted in diminished form for about 2 years. Other similar after-effects have been reported from time to time. For example at the Navy Johnsville centrifuge, a volunteer experienced persisting dizziness and postural imbalance following 12 Gx exposure. More recently, Groen and colleagues (24), in the Netherlands, reported dizziness and postural imbalance in some subjects following one to two hour duration of 2Gx-3Gx.

Because aircraft do not expose pilots to high lateral G, their effects have not been not well-established. However, lateral G is of concern because internal organs such as the heart, lungs, kidney contents, stomach contents will be displaced relative to one another due their different specific gravities. Moreover, the rate at which the CNS receives G-induced signals from internal organs is sufficient to play a significant role in perception of verticality (1, 51, 52).

Tilt Perception. Since the observations of Mach (44, 45), first reported in 1873, the fact that lateral G produces an erroneous perception of roll tilt on centrifuges has been documented many times. The dynamics of tilt perception are very important in attempting to model the perceptions of race car drivers and of pilots in aircraft. The GIF tilts in roll approximately 79deg. during 5G lateral (Gy), but roll perception (subjects seated upright relative to gravity) lags far behind the physical stimulus (8, 13, 19, 20, 54, 62). In darkness on a centrifuge, the time constant (TC) of tilt perception is about 15 seconds. In a lighted room, perceived tilt (on average) is midway between the 'visual vertical' and the GIF (65). Assuming roll-tilt perceived by a driver is reduced by 75% due perceptual lag, perceived roll would be about 20deg. as illustrated in Figure 2b, less than the 79deg. GIF tilt (Figure 2a). Figure 2b also illustrates (upper right panel) estimated 8deg. pitch perception of a Formula One (higher acceleration) car driver during 2.5 sec of starting acceleration, based on simulation of aircraft catapult launch (10).

There are well-known individual differences (e.g., some individuals are influenced by the visual framework and others are more influenced by the GIF). The incidence of motion sickness in motion simulators and in various forms of transport seems to be higher in people strongly influenced by the Visual Field than in those more influenced by the GIF (42a, 42b). Individuals with Motorists Disorientation Syndrome are sometimes helped by devices that block their lateral view (56). Research into the Visual-Field dependence of drivers may be interesting.

In everyday life, a lag in tilt perception is unacceptable. Normal postural dynamics require very quick detection of head and body tilt, even in darkness. Patients without this ability are in serious trouble (2). Quick detection of roll-tilt, for example, depends upon a roll signal from the semicircular canals and concordant messages from the otolith system and other gravity sensors (17, 29).

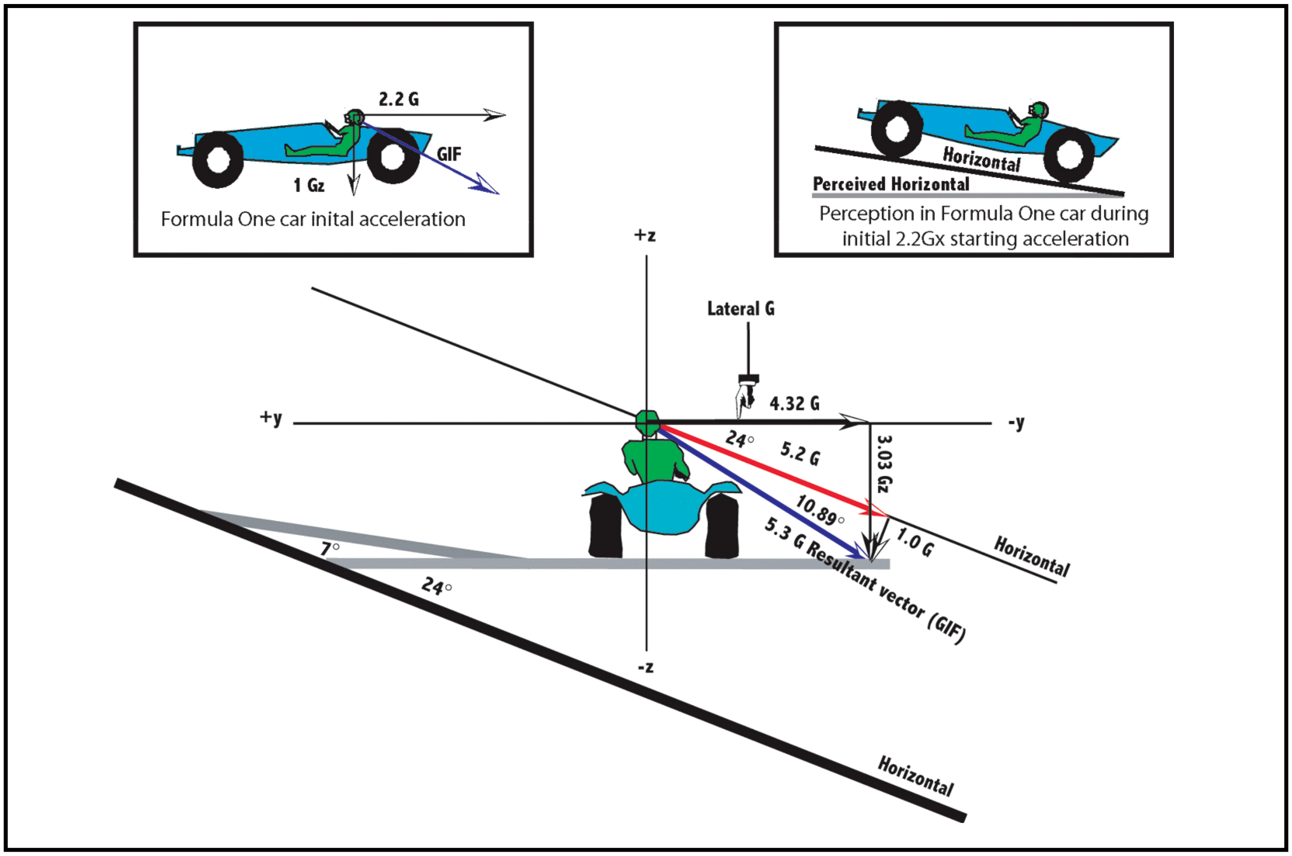

Figure 2b. Although the Gif is Tilted 79deg. relative to gravity on the 24deg. bank of Turn 2, lag in tilt perception could yield perception of zero body tilt and a horizon tilt less than GIF tilt. Upper right panel conceptualizes a Formula-one car driver during 2Gx starting acceleration on the 5deg. bank of the Front straightaway. GIF Pitch Tilt is 60deg., but due to perceptual lag, 10deg. pitch-up tilt of body and horizon is illustrated, based on findings of Cohen et al (10). In carrier catapult launches, pilots experience 4Gx for 3.2s, and in darkness the pitch-up perception persists for about 20s which has resulted in controlled flight into the ocean.

A model capable of predicting the perceptions of race car drivers and pilots will be very complex. An interesting approach to modelling taken by Jan Holly assumes that the CNS is a perfect processor of angular and linear information provided by the semi-circular canals and otolith systems (39, 40). Using estimates of lateral G calculated from car speed and turn radius, Holly has developed a model of turn and tilt perception during 10 consecutive laps on the TMS with the interesting result illustrated in Figure 3. The graph in Figure 3 represents roll-tilt perception extracted from the output of a fully three-dimensional (3 linear, 3 angular) simulation.

While inspecting Figure 3, keep in mind that drivers are focused on other cars (front and rear), path and slope of track, but they also are aware of fuel and engine gauges, body temperature in cooling vests, pit stops, and bodily needs during 600 laps. Figure 3 shows predicted roll tilt perception for a subject who is focused on indicating perceived tilt. It illustrates false data reported to the Central Nervous System (CNS) by non-visual motion and tilt sensors that must be overcome with visual information and training (15, 26, 48).

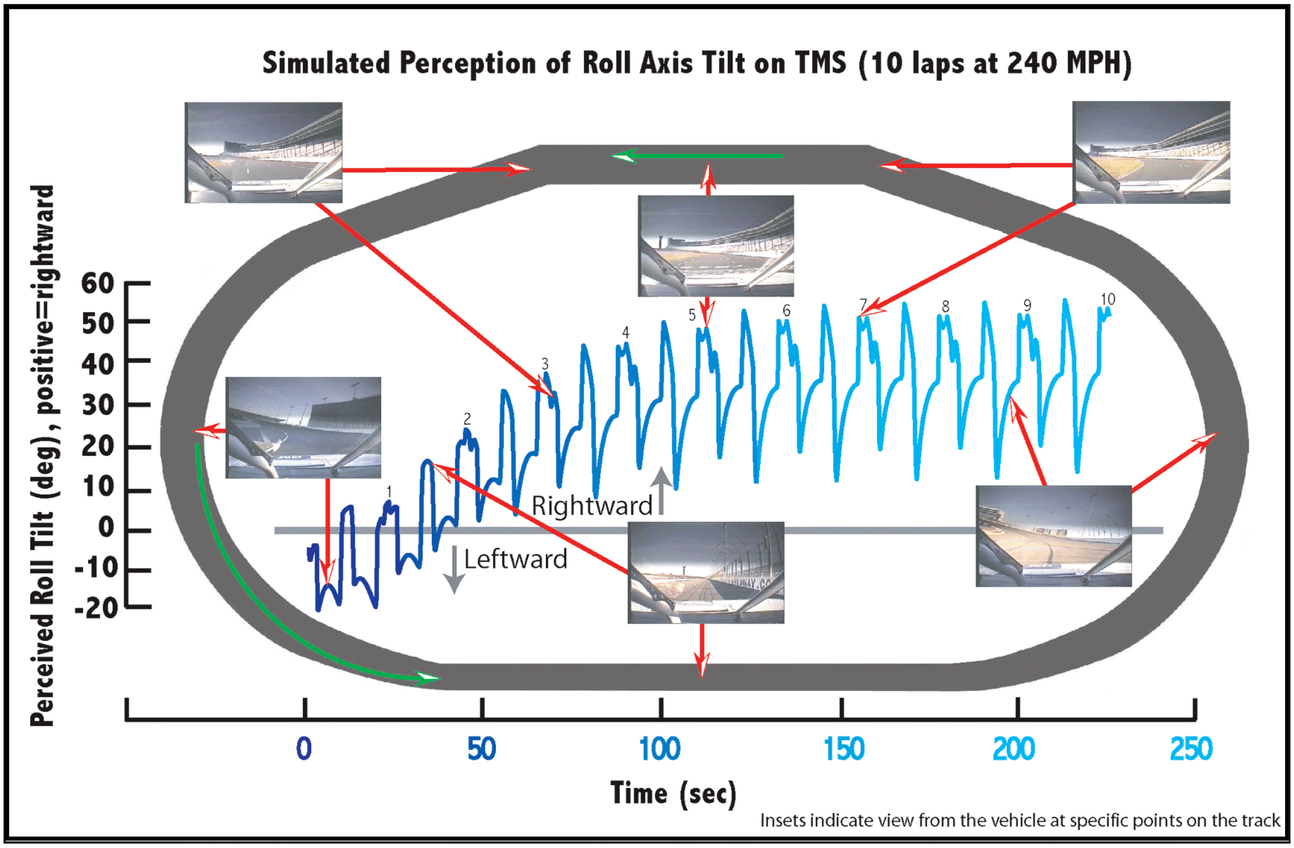

Figure 3. This graph of the output of Holly's model which included perceptual time constants based on the lag in perception of verticality when the GIF tilts relative to an upright subject, and perception of rotation as influence by velocity storage (9).

Models can be used for: a) estimates of effects of consecutive laps which can be compared with reports from drivers; b) predictions of particularly dangerous portions of highways could be compared with Highway accident records; c) selecting strategies in races; d) evaluating race track design, etc.

Dizziness without High G exposure. Dizziness, blurred vision, stomach queasiness and postural imbalance are common during and after rides in land, sea and air vehicles, in amusement park and laboratory devices, including some in which the subject is stationary. Moving visual fields can produce perceived whole-body motion (49), motion sickness and postural imbalance after-effects, viz., I-max, flight and ship motion simulators (6, 21, 42 a). Many motion platforms provoke a high incidence of all of these symptoms with G-forces no greater than those encountered in walking and running (15, 25, 28, 34). In fact these symptoms in relatively immobile individuals bring over 100,000 patients each year in the US alone to Otolaryngologists and Neurologists. Watt and colleagues (66) produced motion sickness in subjects who were standing erect and actively oscillating the upper body and head 'en bloc' in yaw for 5 or 10 minutes. During the initial days on orbit, astronauts in 'zero G' restrict head movements by moving head and trunk 'en bloc' to avoid unnecessary head movements which produce 'space sickness (55); brief 'zero G' during parabolic flight produces motion sickness (41b). Following orbital missions, astronauts have postural imbalance that sometimes lasts for many days (5, 57). Alcohol intake (>4 ounces) produces blurred vision and postural imbalance for about 4 hours after consumption (32). Certainly some CART drivers were exposed to conditions that tend to produce spatial disorientation, dizziness and nausea, but why the problem on the TMS on April 27, 2001? Some possible answers based on Aviation Medicine research follow.

G-load change frequency and Motion Sickness. The TMS has two 24deg. banked turns, each 166deg. in length, and two turns in the Front Straightaway each 14deg., totalling 360deg./lap. If lap time is 22 seconds, the frequency of substantial G change experienced is 0.18cps. This happens to be a very provocative stimulus frequency for motion sickness (3, 11, 14, 28, 42a). Recordings of tri-axial accelerometers made during several laps around the TMS will permit better comparison with the literature on stimulus frequency and motion sickness incidence.

Centrifuge Deceleration. Deceleration of a swinging gondola centrifuge produces a disturbing, frightening perception of pitch change (nose down) coupled with pitch tumble velocity much too great for the perceived change in pitch position (29, 38). Paradoxical perceptions and nausea are common in situations that generate conflicting information about motion from different senses (38). When a race car transitions from the 24deg. slope of turn one to the 5deg. slope of the Back Straightaway, the driver experiences angular deceleration coupled with changing GIF roll. Will this transition produce effects similar to centrifuge deceleration?

No, for several reasons: a) The magnitude of the angular deceleration involved is low because the maximum angular velocity in the turn is only about 27deg./s. b) If the angular velocity were greater, the answer is still no, because the Time Constant (TC) of responses produced by the lateral semicircular canals is about 15 seconds, and so the deceleration would be perceived as stopping the turn. (27). c) The earth-fixed visual field, non-visual motion and tilt sensors and active control by the driver combine to yield perceptions sufficient for accurate control of motion.

These factors can be evaluated fairly well on a few existing multi-axis centrifuges with ‘virtual reality’ capabilities in the gondola, but an important condition that cannot be simulated on existing centrifuges is angular deceleration without loss of forward speed. On centrifuges, the sudden drop off in centripetal acceleration as angular deceleration begins produces “pitch forward” otolith and proprioceptive stimulation soon followed by cross-coupled canal-stimulation indicating forward tumble in a subject whose restraint system is discomforting during pitch forward perception (29, 38). Aircraft and race cars frequently increase forward speed as they come out of High G turns, in which information from the visual-vestibular-proprioceptor systems and active vehicular control, in combination, is sufficient for control of motion.

Race Track Research. Figures 4a and 4b are sketches made from an overhead perspective of the TMS Oval, conceptualising Laps 1 and 2 of a race. Think of the TMS as a very large complex centrifuge with a tri-axial gondola at the end of the arm. The gondola contains sets of triaxial linear and angular accelerometers, and a recording system for several perceptual and physiological responses. A large earth-fixed visual display containing large and small 3-dimensional objects can be made visible or it can be with-held. When visible, the relative movement of the display can be recorded and time-locked to the responses of the subject and to the linear and angular accelerations experienced by the subject.

In Lap 1, the car begins accelerating at the starting line in the Front Straightaway so that speed is increasing to a point in Turn 1 conceptualised in Figure 4a. Figure 4b illustrates Lap 2, a “full throttle” lap in which speed changes are due to controlled skids during which speed is “scrubbed off”.

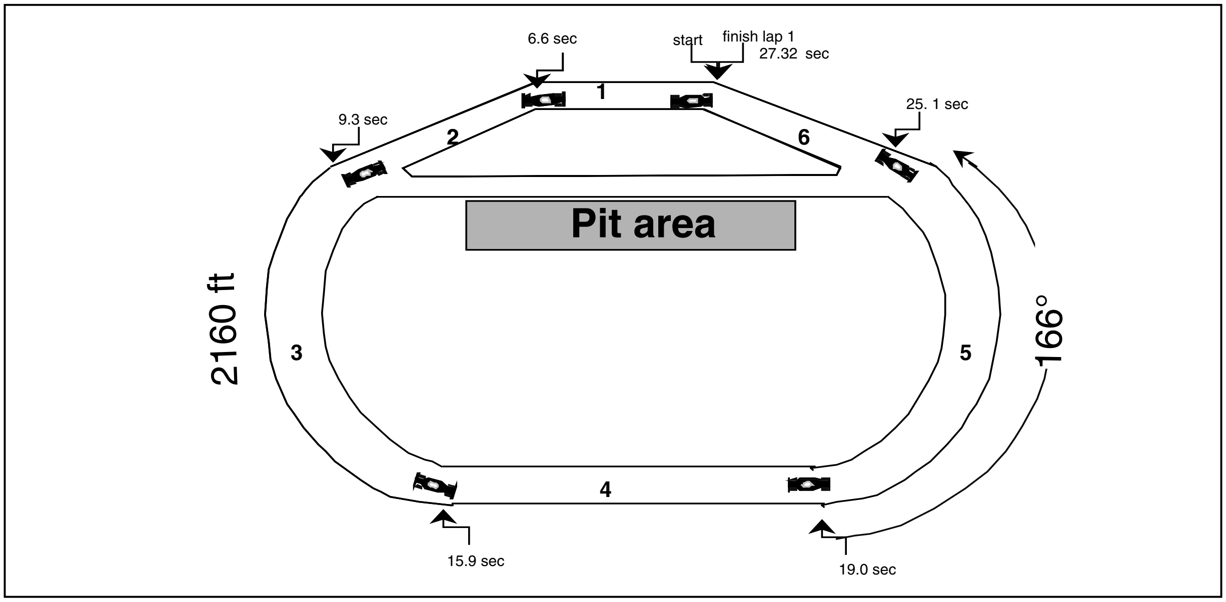

Figure 4a. Assumptions for Lap 1: Starting acceleration of CART cars is 0 to 100mph in 4.2 sec (1.08Gx); speed is 352ft/s (240mph) during Turns 1 and 2; speed on back straightaway is 250mph. Radius of turns 1 and 2 is 750ft.

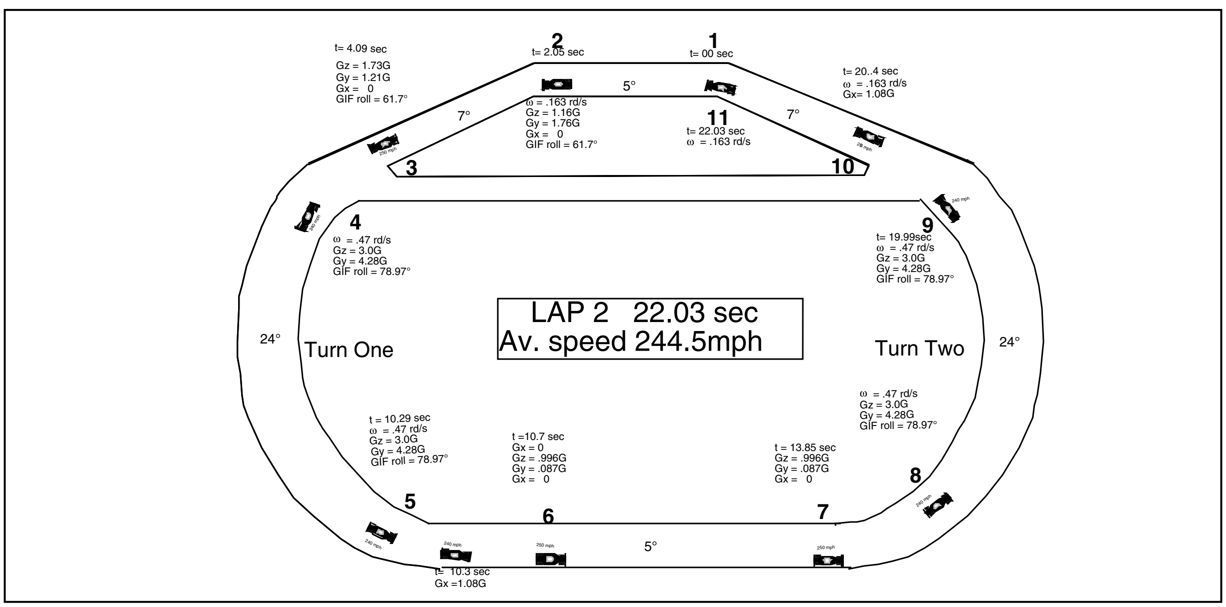

Figure 4b. As lap 2 begins at point one, speed is 250mph. Assume that the Front "straightaway" is driven as a large radius (2250ft) turn with a 5deg. bank. At point 2, the 7deg. bank begins which changes Gz and Gy. At point 4, the bank increases to 24deg. and the turn radius is reduced to 750 ft (Gy=4.3G, Gz=3.0G) so that speed is scrubbed off to 240mph. Between points 5 and 6, the car accelerates at 1.08Gx to 250mph.

Now consider some of the capabilities of this track as a centrifuge:

Dynamic Visual Acuity

What is the influence of an earth-fixed visual background on visual acuity for near objects during self-motion at 20-90 mph and at speeds greater than 200 mph? Studies in which this question was pursued using a 2D visual display on which a "near" moving object was viewed against an "earth-fixed background" on the same flat display indicate that dynamic visual acuity for the "near" object is degraded when a stationary background is visible. However, inferential evidence suggests that visual pursuit (36,41) and dynamic visual acuity for a near object viewed against a more distant earth-fixed background is better than when no background is available (35).

What are the short- and long-term effects of exposure to cyclic sustained complex angular and linear acceleration on every system of the body? Note the interesting transition from perceived right tilt in the early laps to left tilt in later laps in a total of 10 laps illustrated in Figure 3.

Disorientation-error Aircraft Accidents (DAA).
The typical analysis of DAA centres on available visual reference, distraction from cockpit instruments and GIF. The direction of the GIF is usually accepted as the pilot's erroneous perception of aircraft attitude when visual reference is absent (4, 10, 63, Paper 10 of this meeting). While this is a useful "first guess", known lags in verticality perception must be better understood. A model that predicts verticality perception during sequences of complex changes in the GIF will be of great value.

Feasibility of Race Track Research.
The TMS and other race tracks seem to be available for trial runs by interested individuals on non-racing days. Four laps at speeds 140-160mph can be driven as a passenger (61). A triaxial linear and angular acceleration package with recording system can be installed in a Team Texas NASCAR style car. These cars are used for "tourists" and for racing schools. Alternatively, a car owned by an individual or research institute can be equipped with sensor and recording packages for linear and angular accelerations, visual scene and perceptual and physiological responses. The cost of purchasing and operating a very good car, including maintenance, will probably be less than the cost of operating a large multi-axis centrifuge.

Summary and Conclusions.

1. The problem reported by drivers on 27 April was probably not due to G-LOC. The most probable cause was the stress and fatigue that is generated when whole-body motion is actively controlled in spite of mixed sensory messages about the state of self-motion and self-tilt.

2. Drivers experience cyclic high G for several hours during races. Track races are run on ovals like the TMS, some shorter some longer with banks on the turns some less than some greater than those of the TMS. All turns are counterclockwise (as viewed from above). Thus track races are similar to a very large centrifuge except for straightaways between turns and bank angles that do not maintain the head-to-seat GIF alignment that is present in swinging gondola centrifuges and in aircraft during co-ordinated turns. During turns on track races, the driver experiences lateral G similar to centrifuge subjects who remain upright relative to gravity or in some fixed position relative to gravity (8, 12, 16, 20, 30). Each of these different fixed positions on a centrifuge yields different roll and pitch perception dynamics. On swinging gondola centrifuges, subjects perceive roll even though the roll plane component of the GIF remains aligned with the head-to-seat axis (38, 16, 64).

3. Drivers may not have reported problems before 27 April for the same reason pilots withhold information from Flight Surgeons. Pilots want to retain Flight status, and drivers want to continue racing. Discussion with the two drivers who were unable to complete practice laps prompted other drivers to admit similar symptoms. Those who did not experience similar symptoms may have been showing solidarity with the affected drivers or have been concerned about racing in conditions where anyone could suffer similar symptoms. The annual income of top drivers is millions of US dollars and Euros.

4. The cooling vest worn by drivers suggests that a vest containing "tactors" may be feasible. Pilots wearing tactor vests activated by attitude and other instruments can maintain control of aircraft while blindfolded or under other degraded visual conditions (46a, 58, 60). Drivers could be alerted to the position of overtaking cars, information that would supplement information from the spotter who communicates with the driver.

5. Although a model to predict the spatial orientation perceptions will necessarily be very complex, it will be no more complex than a model that will predict responses of an individual in every day life activities. Individuals with disorders of the spatial orientation system perceive unreal tilts and movements that are very disturbing, and also very perplexing to the physician.

6. Drivers are typically medium height or less, trim individuals who maintain physical fitness regimens. However, considering the long sustained cyclic G experienced by drivers, the incidence of disorders that potentate dizziness, such as Benign Positional Vertigo and neck injury (2, 47), should be carefully monitored.

7. The typical analysis of Disorientation-error Aircraft Accidents centers on available visual reference, cockpit distraction from instruments and GIF. The direction of the GIF is usually accepted as the pilot's erroneous perception of aircraft attitude when visual reference is absent. A model that predicts perception of verticality during sequences of complex changes in the GIF will be of great value in analysis of aircraft accidents and driver challenges in car races.

8. Models consistent with: a) dynamics of the sensory systems critical to spatial orientation and control of motion b) anatomy and neurophysiology and c) quotidian "functionality" (37, 59) have been critical to advancing understanding of spatial orientation perception and the problems of patients. Information from research in which responses have been measured in particular time segments of the "frequency domain" is a necessary step toward modelling three-dimensional path-of-movement perception during 10 or 20 laps in which two straightaways (one with two 14deg. turns in it) are interposed between two 166deg. turns. Description of perception and dynamic visual acuity during early, middle and late sequences of laps in a total of 600 laps on the TMS could provide empirical data for testing models of responses during complex activities during long time periods.

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Disorientation in Helicopter Ditching and Rigid Inflatable Boat Capsizement: Training is Essential to Save Crews

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Summary

This paper discusses the disorientation problems of escape from a rigid inflatable boat (RIB) that has been capsized. It makes comparisons with executing a ditched helicopter underwater escape and emphasizes the need for realistic training for both RIB and helicopter crafts. Although very poor records are collected on RIB capsizements, each year there is a small but significant loss of life and many close calls. A paper at the Royal Institute of Naval Architects in 1998, reported 13 deaths from an accident involving the Sea Gem in 1965, but gave no further details (Reference 5). The Transportation Safety Board of Canada reported the case of the G.R.1 FRC (Reference 3) launched from the Gordon Reid off British Columbia, which grounded and flung the three occupants over the rocks and back into the water. Miraculously, all three survived. Rigid inflatable boats or fast rescue crafts (FRC) are used by every Navy in the world, as well as many other paramilitary and commercial marine organizations. In 1998, it was reported that the US Coast Guard alone operated over 700 FRCs (Reference 5). To date, no one has examined the problem of escape from such a vessel after it has been capsized, although Oakley has examined the pros and cons of wearing head protection while operating small, fast boats (Reference 2). This paper discusses a recent experiment conducted by Survival Systems to examine the problems of underwater escape from a capsized FRC.

Introduction

The greatest danger faced by crew and passengers in a fast rescue craft (FRC), otherwise known as a rigid inflatable boat (RIB), is capsizing and death from drowning. However, very poor statistics are kept on such incidents. FRCs are used around the world by military and commercial marine operators. There is anecdotal evidence that accidents are occurring, but specific details into the cause or reliable record keeping does not seem to exist. Why this is so is unclear, but it is postulated that FRC operations occupy a somewhat orphan position in marine operations. Unless a death or collision occurs with a marine vessel, or the national Coast Guard is involved, then the incident is not recorded or analyzed as a statistic. It simply is placed in a commercial company or naval safety record after local investigation.

In the event of a sudden capsizement, the crew and passengers are hurled around the FRC. The most likely scenario is that the weather will be cold and miserable, and the crew will be taken by surprise. Thus, no one will have taken a good handhold or may, for instance, be in the process of attempting to drag a victim into the FRC, and therefore have no handhold at all, and the coxswain may be concentrating on a complex maneuver to hold the boat steady, (Reference 1) or a complex geophysical survey (Reference 8). Therefore, people are likely to be physically injured by contact with parts of the FRC and will most certainly be disoriented from inversion and submersion. Sudden immersion in cold water will also produce an

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uncontrollable gasp reflex even if a good protective suit is worn. At present, with no training in inversion and immersion, only diving skills, comfort underwater and some luck will prevent someone from drowning.

A classic example of such a tragic accident was the loss of the FRC No. 244 from the CCGS Sir Wilfred Grenfell in October 1989 where all crew perished during the process of attempting to rescue one body surfer at Middle Cove, Newfoundland (Reference 4). Capsize of FRCs is not particularly a rare event in Canada. Records from the Transportation Safety Board of Canada from 1975 to 2000 revealed three additional incidents. In August 1995, a Survival Systems Limited Class 3 FRC capsized in very rough seas at the Halifax Harbour entrance; the five people on board were thrown overboard, rescued, hospitalized, and later released. The coxswain suffered serious injuries to the face, having been hit by the steering wheel and console in the overturn. In March 1998, a Class 2 FRC was involved in whale watching off Vancouver Island; it heeled sharply and spilled four persons into the water, only two people survived this accident. In May 2000, the Class 5 FRC from OSV Hebron Sea capsized off the Sable Island gas field, Nova Scotia; both crewmembers were rescued and med-evacuated to Halifax where they both survived. Finally, a newspaper reported in October 2000, that seven Canadian sailors from HMCS Charlottetown were rescued when their rigid-hulled inflatable boat capsized off Norfolk, Virginia (Reference 6).

To combat this problem, the manufacturers of FRCs have fitted CO_2 inflated self-righting bags activated from the transom. The objective is for the survivors to float up into the air pocket that is theoretically created by the inverted FRC, take a breath, make their way to the stern and activate the self-righting bags. However, the chance of a disoriented survivor making his/her way to the stern and operating the inflation toggle is not as easy in practice as it sounds in theory. Let us review some of the testimonies of people who have survived an FRC capsizement.

Righting systems do not always work!

The rest of the crew (I saw 3) drifted away from the FRC… After that, I banged on the FRC to see if any one might be trapped under the boat to which I got no reply. I then attempted to find and pull the self-righting mechanism. When I found the pull cord and pulled at first nothing happened. After I found the pull cord the second time I jerked it harder than the first time and all that happened was an air release from under the boat, which I presume was the inflation mechanism….Then I waited for the other FRC, which could be seen coming toward me. When the FRC came alongside the upturned FRC, I sent them towards the rest of the crew in the water…

The occupants have been suddenly inverted and submerged in water (which is often cold); they are disoriented and have only a limited breath hold ability.

Now the FRC was starting to flip, the port gunnels went under the water and all members either jumped or were thrown from the vessel.
While under the water I noticed that the FRC was coming over on top of me so I reached up and grabbed onto the rope on the gunnels and pulled myself clear. When I was coming to the surface I saw one of the senior observers going over the top of me and willingly staying with the overturned vessel that was now being towed by the steamer. I immediately looked around and did a quick head count and asked if all individuals were okay, the responses were all positive.

The FRC started to list to port. It was a little slow, then the next thing I knew I was in the water. I don't think I ever got over the seat.
I was face down in the water and under the 'new' port side back corner from about the waist down. I think I was trying to push off the FRC with my feet, and swim/push with my arms. Apparently, the FRC was being pulled port so I wasn't making much progress. I saw someone float by, so I grabbed their feet and twisted out and to the surface.

They are further encumbered by bulky, buoyant survival suits and lifejackets and have no additional underwater guidelines to locate the toggle. Furthermore, if (s)he has never before experienced being rapidly rolled over and submerged two meters underwater, the event may be such a terrifying experience that it causes panic and drowning. When an incident occurs, the coxswain may be standing or sitting. This is probably exactly why one passenger was trapped under FRC Uruao and drowned in March 1996. The craft was in the process of conducting whale watching tours off the Kaikovra Peninsula when there was a catastrophic failure of the buoyancy bags, and it rapidly capsized. Also, why two US Coast Guard officers died in an FRC capsizement on the Niagara River in March 2001. (Reference 1)

Two die as US Coast Guard vessel flips: Rogue wave swamps patrol boat

A US Coast Guard boat patrolling the Niagara River along the US-Canada border capsized and two of the four crewmen died Saturday after floating for hours in the icy waters of Lake Ontario.
"A four-foot (1.2 metre) wave hit the bow of the boat, swamping it and flipping it over," said Adam Wine, chief petty officer at the Coast Guard's Buffalo station.
The 6.5 metre, rigid-hull inflatable was found floating bow up along the lake shore about 1.5 kilometres east of the mouth of the river, and the crewmen were rescued soon after midnight about five kilometers northeast of the river, Wine said.
Petty Officer Scott Chism, 25, a boatswain mate from Lakeside, Calif., and Seaman Chris Ferreby, 23, a native of Morristown, N.J., were both suffering from hypothermia when they were pulled out of the water. They were listed in critical condition through the night but both died Saturday morning. (The Chronicle Herald, Halifax, 25 March 2001)

Therefore, Survival Systems Training Limited's President and prior Training Manager, John Swain, theorized that it might be possible to use the current helicopter underwater escape trainer to:

(1) Incorporate a FRC Ditching Simulator

(2) Investigate the human factors involved in an escape from a FRC

(3) Design a simulator that could be used to train coxswains and crew how to make a successful escape from a capsized FRC.

This scientific report will describe the work undertaken by the staff at Survival Systems to complete this experiment.

Method

Initial problems experienced with the design of the FRC Ditching Simulator.
Over a 12-month period, several prototype FRC hulls and consoles were designed. The parts for the self-righting system were manufactured, but all were subsequently abandoned. The principle problem was that it was not possible to design inflatable self-righting bags that would overcome the buoyancy pods installed on the helicopter underwater escape trainer and produce a surface-righted simulator at the surface.

Solution to initial righting problems experienced with the design of the FRC Ditching Simulator.
After further experimentation, it became clear that to simulate capsizing and then surface righting, there was no need to install self-righting bags. The simple solution was to sink the helicopter under water escape trainer to a specific depth indicated by the outboard becketed grab lines on the FRC Ditching Simulator. This allowed the downward momentum of the helicopter underwater escape trainer and the upward thrust of the buoyancy pods to invert the simulator replicating an FRC capsizement. Then, after a short period of time, the crew would escape and muster at the stern. The helicopter underwater escape trainer could be then gently raised by the hoist back to the surface of the water, enough for it to rotate back to its original upright

position. Having completed 50 immersions to test that this theory worked in practice, it was then considered safe to proceed to a human factors experiment.

Human Factors Experiment

The helicopter under water escape trainer was adapted to accept the prototype FRC Ditching Simulator (Figures 1 and 2).

Figure 1: Starboard View of the FRC in Survival Systems' helicopter underwater escape trainer.

The helicopter underwater escape trainer was hoisted over the pool, and a series of immersions were conducted with the FRC in an unmanned condition. This was to confirm the correct depth to submerge the becketed grab lines on the FRC, estimate the roll rate; and to establish crane operator and safety diver emergency procedures in the event of a subject becoming trapped.

Physical Positions Prior to Inversion

Once this was completed, three instructors from Survival Systems Training and the author each acted in turn to be the coxswain, the port lookout, and the starboard lookout. Following this, each instructor acted in turn as the coxswain while the other two instructors acted as port rescue staff and then starboard rescue staff; i.e., for each of these immersions, two instructors were leaning over the same side of the FRC holding the inboard or outboard becketed grab line depending on how comfortable they were with their natural reach (one subject was short, 157cm, while another subject was tall, 188cm).

When an incident occurs, the coxswain may be standing or sitting. Therefore, for the coxswain position, half of the immersions were done from the standing position and the other half from the sitting position.

Irrespective of whether the coxswain was standing or sitting, s/he was instructed to hold firmly to the steering wheel and secure his/her feet in the canvas stirrups.

For the lookout positions, each instructor knelt down and held firmly onto the port or starboard inboard or outboard grab lines depending on which position they had been allocated.

Figure 2: View looking forward from the transom showing the coxswain's seat and console.

All the rolls are described as referenced from the stern of the FRC looking forwards so that the coxswain and crew are at 0º. If the FRC rolled clockwise, (i.e. to the right) the starboard lookout would enter the water at 90º and finish rolling at 180º, whereas the port lookout would start the roll in air at 270º, enter the water at 90º and finish at 180º.

The direction of rolls were equally distributed between anti-clockwise and clockwise, and each instructor experienced virtually an equal number of immersions directly into the water; i.e., from 90º to 180º as well as rolls over the top beginning from the air; i.e., from 270º to 180º. Because it was unclear whether there would be an air pocket under the FRC in a capsizement, the helicopter underwater escape system was operated to provide: (a) no air gap, (b) a small air gap where there was just enough room to catch a breath of air, and (c) a greater air gap where it was possible to float underneath the capsized system and breath freely.

For all conditions, on the command: "Ditching!" the instructions were to hold firmly onto either a grab line or the steering wheel (depending on the subject's position). When inverted underwater, two separate techniques were developed to escape. First, from the coxswain's position, it was necessary to hold firmly onto the steering wheel until the instructor was confident that s/he could locate and grab the inboard port or starboard grab line (depending on direction of roll). Once the grab line was located, the technique was to take a firm grip on it with one hand, let go of the steering wheel with the other hand, release the feet from the canvas stirrups and pull oneself around the sponson, and, if necessary, grab the outboard grab line to provide extra leverage to escape. For the port and starboard lookout positions, and the port and starboard rescue positions, the technique was to hold firmly onto the inboard or outboard grab line until the roll had been completed, then simply pull hard on the grab line to lever the body from underneath the FRC.

Each condition was videotaped, and after each escape, each subject had to rate the ease or difficulty to escape on a scale of one (1) to five (5) where "1" was very easy and "5" was very difficult. Furthermore, they had to comment on good or bad techniques that they tried when making an escape. These included:

(a) Technique for ensuring a firm grip on the becketed grab line, and choice of inboard or outboard line.

(b) Technique for locating the inboard port or starboard becketed grab line from the coxswain's position.

(c) Technique for overcoming the buoyancy of the survival suit or using it to one's advantage.

(d) Technique for figuring out the best way to overcome disorientation and make a rapid, effective escape.

Results

A) Individual Escapes from the Coxswain's Position

Individual Escapes from the Coxswain's Position			
Subject	**Condition**	**Ease or Difficulty**	**Comments**
1	Standing	2	Must hold on tight and difficult to locate grab line.
2	Sitting	3	Must hold on tight and difficult to locate grab line.
3	Standing Floating to Top	3	Must hold on tight, lost handhold, and came out on opposite side than planned.
3	Standing Floating to Top with Bigger Air Gap	3	Must hold on tight and air gap is useless.

The ease or difficulty ranged between a rating of "2" and "3".

The subjects in the first series of individual escapes reported several problems with escape as follows:

i) The first universal comment was that it was essential to hold on as tight as possible and not to relax the grip under any circumstance. Unlike the helicopter underwater escape trainer where the students are strapped in with a 2, 4 or 5 point harness, the students in the FRC are not restrained at all. This is difficult enough to prevent being flung around by rotation and inrushing water for the lookout who enters the water directly, i.e. from a 90º position to a 180º position in a clockwise direction, but extremely difficult for a person on the opposite side of the craft who starts at 270º and rotates clockwise around to a position of 180º underwater.

ii) The second universal comment was that inrushing water contributed to a violent roll-over, and it was essential to hold onto the steering wheel and the grab lines as firmly as possible. In the normal helicopter underwater escape trainer, the in-rushing water is not as violent, because there is the windshield, door, and fuselage panels providing some direct protection. Loss of handhold, as occurred in subject number 3's first immersion, resulted in the subject only barely being able to escape, because the buoyancy of the suit took charge of the direction of underwater movement, which was in the opposite direction to the intended path of escape. The subject found his way out by good luck rather than by good management.

iii) The third universal comment was that the buoyancy of the suit made escape much more difficult.

iv) The fourth comment was that, from the coxswain position, it was very difficult to reach the inboard grab line from either the standing or sitting position (while maintaining a grip on the steering wheel for primary reference). The reason for this was simply that they were placed too far apart for even an extended reach.

v) The fifth comment was that to allow oneself to "float to the top" to access the air gap was not as easy to do in practice as it was in theory. The disorientation effect and the urgent desire to swim from underneath the FRC module, even if the subject was swimming in the wrong direction, tended to override the alternative action, which was to stay calm and relatively still and allow oneself to float up and find the air gap. The other problem is that the air gap may not exist or be difficult to find. Overcoming the disorientation and making the escape, rather than searching for the pocket of air, appeared to be a more practical objective to aim for in escape.

There were no reports of not being able to get the feet out of the canvas stirrups fitted at the coxswain's position.

B) Individual Escapes from the Port Lookout Position

Individual Escapes from the Port Lookout Position			
Subject	**Condition**	**Ease or Difficulty**	**Comments**
1	270º - 180º Roll Anti-clockwise	2	Hang on tight and buoyancy of the suit.
2	270º - 180º Roll Anti-clockwise	2	Wedge in between right foot and right hand and buoyancy of the suit.
3	270º - 180º Roll Anti-clockwise	2	Hang on; poor purchase to pull out; and buoyancy of the suit.
1	270º - 180º Roll Clockwise	3	Hang on tight and buoyancy of the suit.
2	270º - 180º Roll Clockwise	3	Hang on tight and buoyancy of the suit.
3	270º - 180º Roll Clockwise	3	Let go inboard painter and hold firmly to out board painter; airbrake cable close; and buoyancy of the suit.

The ease or difficulty ranged between ratings of "2" for the 90 degrees of roll to "3" for the 270 degrees of roll.

The subjects in the second series of individual escapes reported four basic problems as follows:

i) First, there was the disorientation effect caused by the buoyancy of the suit.

ii) One subject suggested that, from the kneeling position, the body was less likely to be washed around the FRC if it was wedged between the sponson and the position taken up by the right foot, pressed firmly into the curvature of the sponson and the deck, and the right hand which gripped the inboard grab line.

iii) One subject cautioned that there was little purchase available to pull oneself out if the grip was maintained on the inboard grab line. He suggested that, at the first indication of capsize, the victim should grip the outboard grab line.

iv) One subject cautioned on the closeness of the airbrake cable and airbrake rollers when pulling himself out of the simulator.

All commented on the adverse effect of the additional suit buoyancy, especially if the subject had to do a 270º versus a 90º roll into the water.

C) Three Crew Escape from the Coxswain, Port, and Starboard Lookout Positions

Three Crew Escape from the Coxswain, Port, and Starboard Lookout Positions			
Subject	**Condition**	**Ease or Difficulty**	**Comments**
1	Coxswain	1	* See below
2	Port Lookout 270º - 180º Roll Clockwise	3	* See below
3	Starboard Lookout 90º - 180º Roll Clockwise	2	* See below
1	Port Lookout 90º - 180º Roll Anti-clockwise	1	* See below
2	Starboard Lookout 90º - 180º Roll Anti-clockwise	3	* See below and airbrake cable.
3	Coxswain	1	* See below
1	Starboard Lookout 90º - 180º Roll Anti-clockwise	1	* See below
2	Coxswain	3	* See below and lost grip and came out of the stern of the FRC.
3	Port Lookout 90º - 180º Roll	2	* See below
*All subjects reported that they had to hang on tight; that the buoyancy of the suit affected their planned escape route, and that training for the coxswain position should be done separate from training for the port and starboard lookout positions.			

The ease or difficulty ranged between a rating of “1” and “3”.

In the third condition, where all three crewmembers were in the FRC, the principle observations were reported as follows:

i) It is essential to hang on tight.

ii) The buoyancy effect of the suit directed the body in a different direction to that of the intended direction of escape and caused severe disorientation.

iii) The subjects noted that they were very practiced. Even though two subjects now rated the coxswain’s escape as a “1”, it was still the most difficult escape. If the handhold was not meticulously and firmly exchanged from wheel to handhold to grab line, then the chances of disorientation and inability to get out were very likely. As a result, all three subjects recommended that for initial training of the coxswain, only the coxswain should be in the FRC, accompanied by an instructor.

iv) Closeness of the airbrake cable and airbrake rollers could interfere with a safe escape if not guarded.

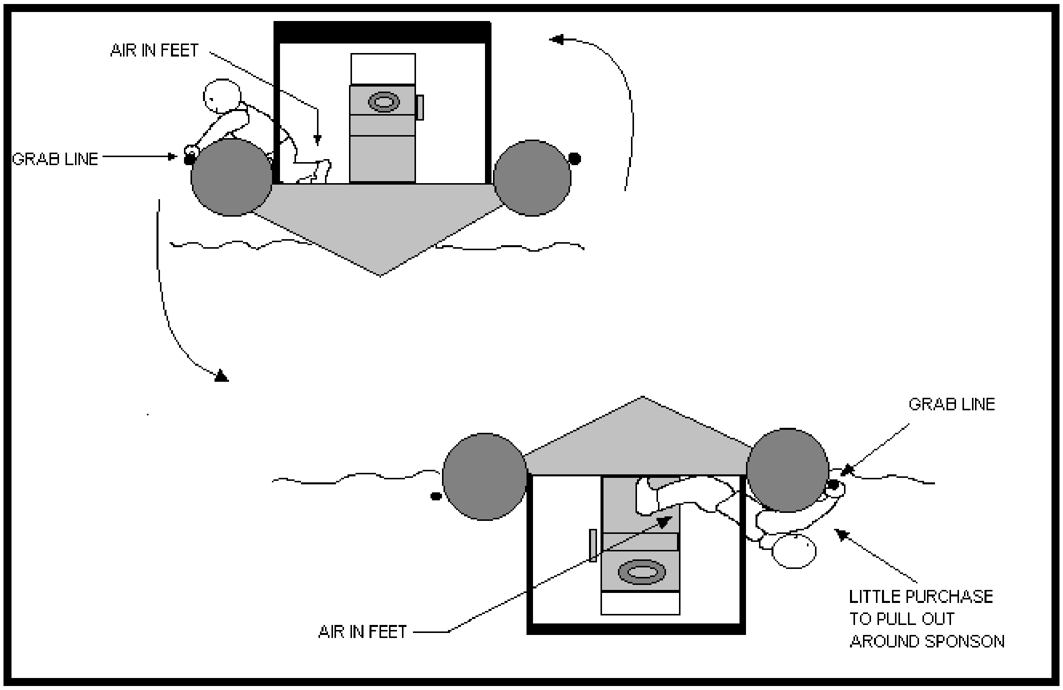
D) Escape from Coxswain and Two Lookouts on the Port or Starboard Sides Undergoing a Recovery

Escape from Coxswain and Two Lookouts on the Port or Starboard Sides Conducting a Recovery			
Subject	**Condition**	**Ease or Difficulty**	**Comments**
1	Coxswain	3	* See below and must keep feet in stirrups.
2	Port – Both on Same Line 270º - 180º Roll Clockwise	3	* See below; line pinched fingers; and airbrake very close.
3	Port – Both on Same Line 270º - 180º Roll Clockwise	3	* See below; line pinched fingers; and airbrake very close.
1	Starboard – Both on Same Line 90º - 180º Roll Anti-clockwise	3	* See below; line pinched fingers; and airbrake very close.
2	Starboard – Both on Same Line 90º - 180º Roll Anti-clockwise	3	* See below; line pinched fingers; and airbrake very close.
3	Coxswain	3	* See below
1	Starboard – On Forward Line 90º - 180º Roll Clockwise	1	* See below
2	Coxswain	3	* See below
3	Starboard – On Aft Line 90º - 180º Roll Clockwise	2	* See below and airbrake very close.
*All subjects reported that they had to hang on tight and that the buoyancy of the suit affected their planned escape route.			

The ease or difficulty ranged between a rating of "1" and "3".

The three observations made in the previous series of escapes were made again: i.e., the requirement to hang on tight, the buoyancy of the suit, and the proximity of the airbrake hose. There was an additional observation that the fingers were severely pinched when two lookouts were pulling on the same line to exert pressure to pull themselves out over the sponson. They also commented that the air in the feet of the suit was dragging the lower half of the body back into the FRC. A technique to counteract this problem needs to be taught when training students.

Figure 3: A schematic to show how air migrates into the lower part of the suit and feet on inversion. This then holds survivor between the edge of the sponson and the deck.



Conclusion

Twenty-eight experimental subject immersions in the helicopter underwater escape trainer FRC Ditching Simulator have been conducted. In addition, 50 additional pre- and post-experimental subject immersions were conducted to assess rates of roll, techniques to hold onto the becketed grab line, and techniques to assist the coxswain to move from the driving console to access the port or starboard buoyancy sponsons. All four subjects were highly trained and are experienced instructors at Survival Systems Training Limited.

The conclusion from this short study is that there are some very obvious reasons why crews of FRCs die when the vessel capsizes. Worldwide, there is a very small number of deaths of injuries from FRC capsizement. However, poor incident records are kept of such accidents and so it is not at present possible to define the incidence. Overall, the disorientation effect of the FRC capsizement is equally if not more disorientating than that of helicopter ditching and inversion. The principle reasons for this are: (a) the subjects are not restrained, (b) the FRC is open to the inrushing water from all directions, rather than having partial protection from a helicopter fuselage, and (c) the excessive buoyancy in the types of survival suits worn by FRC operators renders everyone except for the largest and strongest virtually powerless to control the path of escape.

Whether sitting or standing, the force of the water entry into the FRC, in combination with the rollover, requires that a very firm grip be held onto either the steering wheel or onto one of the handholds on the console. Loss of handgrip causes total disorientation. Then, the buoyancy of the suit exerts forces on the human and drives the person in whichever way the proximity to vertical occurs during the roll. This direction is often contrary to the path intended by the person. This causes further disorientation, because the person is now attempting to swim in a direction opposite to the path of intended escape. In the cumbersome buoyant survival suit, the victim does not have enough dexterity or strength to reverse this direction. Ultimately, and particularly in cold, turbulent water, breath holding time would be reduced, and this would lead to drowning. Loss of foothold in the stirrups for the coxswain only compounds the problem.

For the coxswain to counteract this disorientation, even a firm grip on the wheel or console handles is only a partial solution, because the next step to escape is to bridge the gap between the console and the inboard port or starboard becketed grab line. For most people, this is a long reach even in the upright dry condition of a normal operating FRC. Given the circumstances of being inverted, underwater in poor visual conditions, with cold hands, thick gloves, buoyancy of the suit, and often being driven in the opposite path of intended escape, it is very easy to miss the handhold and again be driven and pinned by the suit buoyancy somewhere against the internal decking of the FRC.

All four subjects agreed that, even under those conditions, the coxswain and the lookouts would be lucky in the disoriented condition to find any air pocket at all. In a rapid inversion, where everyone is in an immersion suit and is taken by surprise, particularly in what will likely be rough sea conditions and cold water, the coxswain in particular has little chance of being able to escape and then move to and muster back aft to right the FRC. Historically, depending on the direction of roll, the look-outs may be flung out clear of the FRC (References 3 and 8). It is, therefore, very important to put a knotted tag line, secured by Velcro, on all FRCs from both sides of the steering console closely following the contours of the FRC to the outboard side of the port and starboard sponsons. Once the coxswain has gripped this line and continues to haul on it, it will improve his/her chance of making an escape. There is also merit in providing FRC crew with helicopter underwater breathing apparatus, particularly if they are working in very dangerous sea states.

For the crewmembers, the problems of escape are related again to:

(a) Buoyancy of the suit

(b) The requirement to have a very determined and firm handhold during the immersion

(c) Being aware that the air that rushes to the feet of the suit will attempt to force the lower part of the body back into the hull.

In the event that the coxswain and crew become disoriented and lost beneath the capsized FRC, the advice to float up and find the air gap is much easier to do in theory than in practice. The skill that must be acquired to stay calm and collected against the psychological terrifying sensation of being trapped underwater with the potential for drowning must be taught. Indeed, the FRC module is a perfect tool for achieving this aim.

From a safety point of view, for training, it is important to put a physical guard in the helicopter underwater escape trainer FRC Ditching Simulator to prevent contact with the helicopter underwater escape trainer air brake system when making the escape. It is also important initially to train students individually to escape from the coxswain's position with one qualified instructor, and until more experience is gained by the instructors about the dynamics of the FRC Ditching Simulator for them to train ab initio crew on a two to one ratio with a safety diver in the pool too. After experience, three students can be trained at a time, providing there is a safety diver in the pool.

Currently, there is no requirement for specific practical training in water capsizement. The US Coast Guard issued a "Manning and Training Guidance for Fast Rescue Boats on US Vessels" instructions in May 2000. This is written in very simple terms and is non-specific.

- A lifeboatman must be competent in the operation of an FRC (i.a.w. 46 CFR 12.10-9)
- Must attend a course (i.a.w. 46 CFR 12.03)
    - Procedures for righting a capsized FRC
    - How to handle an FRC in prevailing and adverse weather and sea conditions

In the author's opinion, it is necessary to insure that in the FRC operator course, the syllabus is revised to include two hours of practical FRC capsizement training in the pool.

Recommendations

1) The FRC Ditching Simulator is considered an excellent device to train FRC crews in the problems of underwater escape after capsizement.

2) Students will find that the coxswain position is the most difficult one from which to escape. This is due to inrushing water, rotation and disorientation, a buoyant survival suit, difficulty in keeping a good handhold, and the long stretch to reach and grasp the port or starboard inboard becketed grab line from the steering console.

3) Therefore, instruction on the coxswain's position should be done on a one-on-one (instructor-to-student) basis with only one student in the FRC Ditching Simulator. A safety diver should also be in the pool during training. See Annex A: Recommended Training Schedule.

4) Ab initio port and starboard lookout crew should also be trained on a two-on-one instructor student ratio, providing a safety diver is in the pool. See Annex A: Recommended Training Schedule.

5) For all escapes, students must be taught to hold on very tight and be aware of the disorientation effect of the inrushing water and rotation of the FRC. Furthermore, they must be made aware of the suit buoyancy and the fact that it may force them in a opposite direction to the intended escape path, and / or force the lower body back into the hull.

6) All students must experience both 90º - 180º rolls and 270º – 180º rolls in a clockwise direction and 270º - 180º and 90º- 180º in a counterclockwise position.

7) The technique to find the air gap should be done with only two students at a time and one instructor and one safety diver.

8) The FRC operator course should be amended to include two hours of practical FRC capsizement training in the pool.

Annex A: Recommended Training Schedule

No. of Students	Run No. & Type	Instructor	Safety Diver
Coxswain only	1. 90º - 180º Anti-clockwise	1	1
Coxswain only	2. 90º - 180º Clockwise	1	1
Coxswain & Port Look-out	3. 270º - 180º Anti-clockwise	1	1
Coxswain & Port Look-out	4. 270º - 180º Clockwise	1	1
Coxswain & Starboard Look-out	5. 90º - 180º Clockwise	1	1
Coxswain & Starboard Look-out	6. 90º - 180º Anti-Clockwise	1	1
Coxswain & Port Look-out	7. 270º - 180º Clockwise Air Gap Training	1	1
Coxswain & Starboard Look-out	8. 90º - 180º Anti-clockwise Air Gap Training	1	
*Coxswain & Full Crew	9. An anti-clockwise roll	1	1
*Coxswain & Full Crew	10. A clockwise roll	1	1

*Port and starboard look-outs exchange positions for these two runs. (Nos. 9 and 10)

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Remote Control of Vehicles

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The remote guidance of vehicles or tools in inaccessible or hazardous environments is of considerable military interest. The control performance achieved with these systems is dependent on the information received by a human operator. Sensors such as Night Vision Goggles (NVG) mounted on the head, or cameras mounted on the vehicle or tool can be used to provide such information, and how many sensors and where the sensors are positioned will depend on the task to be performed. Two experiments have been conducted to assess the effects on performance of presenting monocular, stereoscopic, or enhanced stereoscopic (hyperstereoscopic) information to the operator. One experiment used a head-mounted system to investigate the effects of these viewing systems on depth perception under static and dynamic conditions. In the other experiment cameras were mounted on a remotely controlled vehicle to investigate the effects the different viewing systems on vehicle control. Two tasks were used in this second investigation; one was a driving task, the other a manipulation task. The first experiment showed that there was an effect of motion on the results; depth was estimated more accurately under static than under dynamic conditions. Neither stereopsis nor hyperstereopsis had a measurable effect on depth perception. It was concluded that further experimentation should take place using a more appropriate task. The second experiment indicated that remote control performance was task dependent. For the driving task there was no significant difference between the performance measured under monocular and stereoscopic conditions. In the manipulation task the best performance was achieved using stereoscopic presentation techniques, the hyperstereoscopic presentation of information producing a 38% reduction in task completion time over the monocular time. For both tasks, regardless of whether the differences were significant or not, the better performance was always achieved using stereo rather than monocular presentation techniques. Thus it was concluded that there are advantages in using stereo rather than monocular presentation techniques for remote control tasks. In manipulative tasks the performance gain can be as high as 38%. Such an improvement in performance is clearly of importance for tasks such as bomb disposal and in-flight refuelling. In both experiments some subjects complained of eyestrain when using the hyperstereoscopic systems. Further work should be conducted to determine the optimum convergence setting for different tasks, and the amount of disparity easily tolerated by the majority of the population. On this basis of the above results a new apparatus has been designed to evaluate performance when head mounted displays such as night vision goggles (NVG) are used. The head-mounted apparatus consists of pairs of mirrors to reflect the visual scene into each eye of the individual. The outer mirrors will be positioned to produce effective interpupillary distances (IPD) of 2x, 3x or 4x the individuals IPD. The monocular and 1xIPD configurations will also be investigated. Further experiments are planned which will investigate the relationship between eyestrain and hypersteropsis.

Introduction

There is considerable military and civilian interest in the remote guidance of robotic tools and vehicles. This interest arises because remote control systems are required for use in hazardous and inaccessible environments. The efficiency of control and the performance achieved with these vehicles is highly dependent on the information received by the human operator, and performance advantages can be gained by the correct presentation of this information. Sensors mounted on the head, vehicle or tool can be used to provide such information, and how many sensors and where the sensors are positioned will depend on the task to be performed.

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One aspect that has to be considered when determining the best camera layout is whether or not there will be any improvement in control performance if stereo rather than monocular information is provided to the operator. This question will be of particular importance when the operator's task requires both distance and depth perception (Viveash, 2000).

Initially let us consider binocular and monocular vision. Although two-eyed vision does provide the primary cues to depth perception there are many people with one-eyed vision who have very good depth perception. This is because there are at least seven monocular cues (overlapping contours, or obscuration: motion and linear perspective, texture, light and dark shading, accommodation of the eye and aerial perspective) which are also used in distance and depth perception (Boff and Lincoln, 1988).

Stereopsis is the function of the binocular vision system, which amounts to a detailed comparison of the two retinal images on the basis of parallax geometry, the two retinal images are fused by the brain and yield a vivid and highly detailed perception of three-dimensional space. Typically the stereoscopic threshold varies from 1.6 to 24 seconds of arc. Targets of larger disparities may be seen as double images with no accompanying sensation of depth, or only one image may be seen and the other suppressed (Boff and Lincoln, 1988).

Using two cameras to provide a stereo view on a monitor may result in double images and distortion. These problems arise because the two cameras point to an object at a fixed point (i.e. the cameras are converged to a set distance), and usually unlike the eyes, the convergence of the cameras does not alter when other objects at different distances are observed. As a result whilst the objects in the plane of convergence will appear as a single image, images of objects out of the plane of convergence can appear as a double image, and the scene appears distorted. Furthermore, unlike the visual system, there is no integral mechanism, which automatically suppresses one of the images. Another aspect that has to be considered is that varying the distance between the cameras will also affect disparity and stereoscopic thresholds. Placing the cameras further apart will result in an enhanced disparity. Thus, another aspect that needs to be considered is whether enhanced disparity produces a better performance in all tasks.

Experiment 1

The aim of this experiment was to evaluate what effect the monocular, stereoscopic or enhanced stereoscopic presentation of information had on a subject's depth perception under both dynamic and static conditions. To this end measures of the subject ability to estimate the distance from a Stop sign were made under the two conditions; (a) when the subject was moving and (b) the subject was static and an object (a walking experimenter) was moving.

Apparatus and Method

Twelve subjects took part in the experiment. All subjects were tested for normal vision. That is they were tested for 6/6 acuity without spectacles, or corrected to 6/6 with contact lenses (but not with spectacles). In addition they were tested for normal stereoscopic vision using the Randot and Titmus fly stereoscopic tests (for a description of the tests see Boff and Lincoln, 1988).

The apparatus used to produce the three viewing presentations and the Stop sign target were common to both conditions. Enhanced stereopsis (hyperstereopsis), stereopsis or monocular viewing was produced using a head mounted Variable Latency Asynchronous Display (VLAD). Essentially, for the purposes of this experiment, the VLAD apparatus consisted of two cameras whose individual images were sent to the subject's eyes via reflecting optics. In order to produce hyperstereopsis the distance between the two cameras (i.e. the effective interpupillary distance or IPD) was variable. The Stop sign was a standard road sign with white letters on a red background The word STOP was in capital letters and 560mm wide, each letter was 150.5 mm high, and had a line thickness of 33 mm.

Under both conditions the cameras were positioned at one of four interpupillary distances (IPD). The positions were IPD x 0, IPD x 1, IPD x 2, and IPD x 4. In the IPD x 0 condition the same image was sent to both eyes. When the same image is presented to each eye, i.e. with no disparity, the configuration is known as a biocular presentation. However, in order to draw parallels between the camera configurations and one and two-eyed performance, it will be referred to as the 'monocular' condition throughout this paper. The different experimental procedures used under dynamic and static conditions were as follows.

Dynamic condition: This part of the experiment took place on a 50 metre linear track. The subject was seated on the track trolley that was moved in a straight path using the trolley winch. The trolley travelled at a velocity of 0.22 ±. 0.03 m/s. The vehicle was stopped, by the subject operating a push button at the specified distance (an estimated distance of 3 m) from the Stop sign.

Static condition: In the static condition the subject viewed two markers, one fixed (the Stop sign) and one moveable (an experimenter). The subject's task was to verbally direct the walking experimenter to halt at an estimated distance of 3 m from the Stop sign.

In each trial all the subjects made eight runs at each IPD. Under both conditions the dependent measure was distance between the Stop sign and the trolley or marker. These distances were measured using a Laser Digital Distance Meter (Bosch DLE 30) with an accuracy better than 1%.

Results

A three-way ANOVA was performed on the factors Motion, IPD and Run. Differences between Motion, IPD and Run were analysed using Tukey HSD tests.

IPD	Static	Dynamic
0	5.84	7.76
1	5.69	7.77
2	5.42	8.28
4	5.10	8.00

Table 1: Mean Distance Estimation Scores (in metres)

Significant main effects of Motion ($F(1, 10) = 13.84$, $p<0.01$) and Run ($F(7, 70) = 16.43$, $p<0.01$) were found. All motion judgements were greatly over-estimated with the static condition providing greater accuracy. There were no significant differences between the different IPD's. Mean distance estimation scores are shown in Table 5-1.

Discussion

An observer's ability to judge distance varies with the conditions under which the judgement is made, and one of the most important factor's in this judgement is the amount of information about the conditions available to the observer. The more information available, the more likely the subject is to perceive the distance accurately. Further when the information is inadequate the less accurate the perception and the greater variability in the distance estimate (Sedgwick, 1986). This would, to a certain extent, explain why the distance estimations were both inaccurate and highly variable in both trials. However, although all distance judgements were over-estimated the results show that static judgements produced significantly more accurate estimations than dynamic judgements (those made whilst moving). It is not surprising that a significant effect of motion was reported. In the static condition subjects had a greater number of perspective cues available in their field of view than with the dynamic condition, when they were physically positioned closer to the Stop sign. It is thought that the environment in which the trial was run was rich in monocular cues. This is likely to have largely contributed to the lack of effect between the different IPD's. The use of stereo cues would have been limited at best or not utilised at all.

Conclusion

This experiment demonstrated that there was a significant effect of motion on the perception of depth; depth was estimated more accurately under static than under dynamic conditions. As a result it was concluded that any further experimentation should take place using more appropriate tasks.

Experiment 2

The aim of this experiment was to investigate the effects of the different viewing systems on vehicle control. Two tasks were used in this experiment. One was a driving task, the other a manipulative task.

Apparatus and Methods

Twelve subjects took part in the experiment. The subjects' vision was tested as described in the previous experiment.

A robotic vehicle and stereoscopic viewing systems were common to both tasks. The robotic vehicle used in the experiment was controlled in both velocity and direction using a single joystick. The viewing system was provided by mounting either one or two cameras on a wood and aluminium plate, which was fixed to the chassis of the vehicle.

The inter-camera distance (ICD) was set by a series of parallel fixing holes in the platform and three ICD's were used: 0, 22 and 66 mm. The 0 mm condition was the 'monocular' condition in which a single camera was centrally mounted on the platform. In the 'stereopsis' condition, the 22 mm ICD was the minimum possible separation obtained with the two cameras mounted side by side, and it gave an apparently natural stereoscopic view within this model environment. The 66 mm ICD gave an impression of an 'enhanced stereopsis' condition. A detailed description of the apparatus is provided elsewhere (Viveash et al 2002).

Driving task. The driving task consisted of guiding the vehicle around a circuit through seven pairs of upright wooden markers. These were placed 480 mm apart, a distance 100 mm wider than the car chassis. The car needed to be square on to the markers to go cleanly through the gap. To reduce monocular cues to depth, the markers were varied in size (diameter and height) and their bases, where they stood on the floor, were obscured from view. In the driving task, performance assessment was the total time taken for the run. Each subject made eight runs at each ICD.

Manipulation task. The manipulation task required the subjects to capture five metal rings on a probe attached to the front of the vehicle. The rings were of five different diameters and were hung in a line from a supporting bar. The vehicle returned to a starting position each time a ring was captured. The probe was asymmetrically mounted on the vehicle and rose at an oblique angle, so that it was impossible simply to establish visual alignment between the probe and the ring, and then advance the car. Instead, subjects found it necessary to exert continuous control, rather than simply executing a pre-programmed movement. In the manipulation task, assessment was based on the total time taken to complete the task.

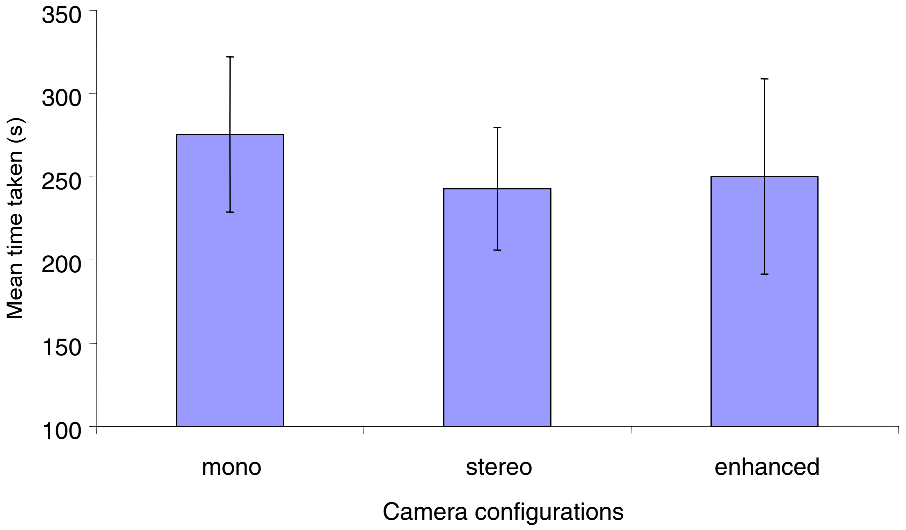
After completing both trials the subjects were presented with a questionnaire that asked them to rank order their preferences for the three ICD's used in the experiment, rank order 1 being the preferred choice.

Results

The main aim of the experiment was to assess the effects of three different camera configurations on vehicle control performance. The mean data for the driving task are shown in Figure 1 and those for the manipulation task in Figure 2.

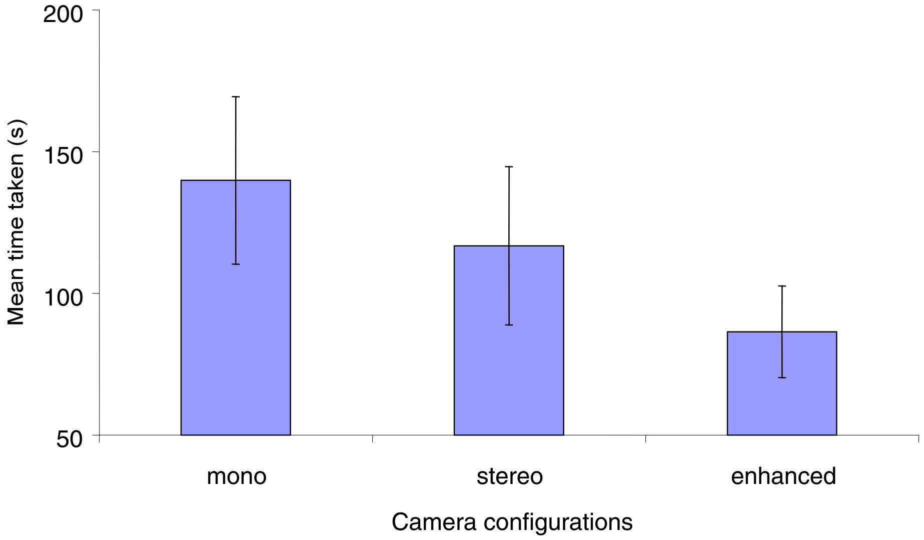
Driving Task. There was no significant main effect due to the different visual conditions. Mean times for the driving task at the three ICD separations are shown in Figure 1. The number of markers knocked down under the three display conditions varied very little (19±2).

Manipulation task. There was a significant main effect of camera configuration on the time taken ($F(2, 14) = 10.06$, $p<0.01$), and post-hoc comparison showed that monocular and stereo presentations resulted in significantly longer task duration's than the enhanced disparity presentation. Mean times for the three ICD configurations on the manipulation task are shown in Figure 2. It was also noted that the subjects had the greatest number of unsuccessful attempts to remove the rings under monocular presentation conditions and the least number under the enhanced disparity condition.



Mean time to complete in the driving task experiment. Figure 1

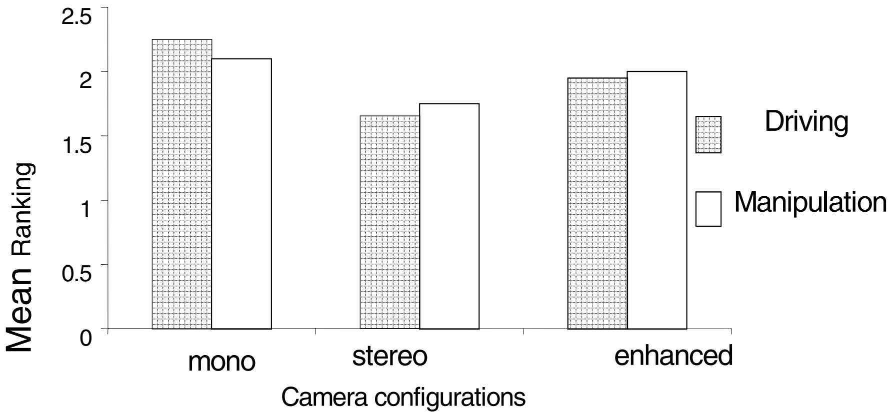
± standard error bars shown



Mean time to complete in the manipulation task experiment. Figure 2

± standard error bars shown

Subjective
Rankings of the preferences for the methods of visual presentation for the two tasks are shown in Figure 3, in which lower scores indicate stronger preference. Although better performance was obtained in the enhanced condition than in the stereo condition, several subjects commented that it gave them feelings of eyestrain.



Subjective rankings Figure 3.

Discussion

The results confirm that the best method of task presentation (monocular or stereo) for a given task is task-dependent. In the driving task experiment there was no significant difference between the time taken to complete a circuit for any form of presentation. In the manipulation task experiment, however, stereoscopic presentation gave significantly better performance than monocular.

The negative outcome for the driving task experiment was not unexpected, because others have had a similar result (Gold et al,1968). Such a result is thought to arise when tasks are performed in environments that are so rich in monocular cues to depth that stereopsis provides little additional information. This was disappointing in this particular trial because particular care had been taken minimise the monocular cues.

The results from the manipulation task clearly demonstrated an improvement in control performance arising from stereoscopic presentation, which reduced mean task time by approximately 16%. Moreover, there was a further improvement in performance from enhanced stereopsis presentation, which decreased task time by 38%, in comparison with the monocular condition. Other experimenters have also shown improved performance with stereopsis in manipulation tasks (Smith et al, 1979).

In the subjective assessments the majority of subjects preferred stereoscopic over monocular presentation. The enhanced stereoscopic presentation, although more popular than the monocular presentation, was found to cause feelings of eyestrain, which would make it difficult to use for long periods of time. There were no comments about the distortion of the scene, even though such comments have previously been reported for cameras converged to a point near to a vehicle (Nagata, 1996) and not to infinity as in this trial. Nevertheless, as expected, double images were seen in the foreground when viewing the enhanced presentation.

The fact that some subjects complained of eyestrain when using the enhanced stereo presentation indicates that a further investigation of enhanced stereo techniques and eyestrain is required. This investigation should determine the optimum camera convergence angles for a variety of tasks and the degree of disparity easily tolerated by the majority of the population.

Another point to note is that performance was never worse for stereo rather than monocular presentation and there is, therefore, no indication that there is ever a disadvantage to using stereo presentation techniques for remote control tasks. For manipulative tasks performance gain may be as high as 38%, and such an advantage is clearly of importance for tasks such as bomb disposal and in-flight refuelling.

Conclusions

This second experiment has demonstrated that: (1) The relative advantage of stereoscopic over monocular presentation is task-dependent; (2) There was no significant difference in control performance between stereo and monocular display presentations in the driving task; (3) There was a significant difference in control performance between stereo and monocular display presentations for the manipulation task; (4) In both trials, a stereoscopic display always resulted in performance that was at least as good as with a monocular display.

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Spatial Disorientation: Causes, Consequences and Countermeasures for the USAF

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USA

SUMMARY

Spatial disorientation (SD) remains a serious drain on USAF resources and personnel. During the ten-year period of 1990-1999, the USAF experienced 36 SD-related Class A mishaps costing a total of $557M and the loss of 44 aircrew. SD is the single most common cause of human-related aircraft accidents. The causes of SD are complex and require an understanding of the types of SD, the physiology and psychology of flight, and the way pilots train for the prevention of SD. Research has shown there are three distinct types of SD—unrecognized, recognized and incapacitating. Each type impacts the pilot in a different way, and each should be thoroughly understood by the pilot before he or she experiences them in flight. Results from a study of the Post-Roll Illusion (Type I), the Graveyard Spin Illusion (Type II), and a report from a pilot who experienced the Giant Hand Illusion (Type III) is presented. Spatial orientation training techniques are included. Finally, the USAF's Spatial Disorientation Countermeasures Program, designed to reduce the number of SD mishaps, is also presented. This program emphasizes shared knowledge across all flying communities, including research in the areas of attitude awareness (visual and vestibular), multi-sensory integration (3-D audio and tactile stimulation), and both ground-based training and flight-based demonstrations.

Although the phenomenon of spatial disorientation (SD) has been described and documented by many, both researcher and aircrew, since the earliest days of aviation, a complete understanding of the complex mechanisms and interactions has remained elusive. The economic consequences alone of SD are enormous, both in cost of lost aircraft and cost of training new aircrew. This paper will provide examples of different types of SD, the interrelationship of SD to loss of situational awareness (LSA), and a brief summary of the US Air Force Research Laboratory's current SD Countermeasures program.

DEFINITION AND TYPES OF SD

One of the most difficult aspects of the SD problem lies in categorizing and defining SD in a manner agreed upon by researchers (Lyons, Ercoline, Freeman, and Gillingham, 1994). Without a precise definition, one cannot be certain that a particular incident qualifies as SD, or is another phenomenon altogether. Accordingly, the most widely used general definition, one that has been accepted by a large number of countries and which will be used here, spatial disorientation (SD) refers to:

> A state characterized by an erroneous sense of one's position and motion relative to the plane of the earth's surface. (Benson, 1978)

This general definition can be slightly modified with words more commonly used by pilots, flight surgeons, and flight physiologists. The modified operational definition is:

> An erroneous sense of the magnitude or direction of any of the aircraft control and performance flight parameters. (Gillingham, 1992)

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

Another difficulty regarding categorizing SD lies in the measurement/yardstick used when determining the nature of the SD condition. For example, SD can be broken into misperceptions due to the stimulation of the vestibular, visual, proprioceptive, and cognitive groupings, depending upon the level of stimulation provided to each human function. Each system requires a complex coordination to take place between the appropriate sensory end organ and the human's central processing unit (i.e. the brain). It becomes even more complex when several sensory modalities are used.

A commonly accepted system of categorization uses a more functional approach. The first grouping, describing phenomena that are unrecognized by the individual, is appropriately named Type I SD. The second functional group encompasses recognized phenomena and is labeled Type II SD. The last, and less well accepted grouping includes what are classed as incapacitating events and are listed, surprisingly enough as Type III SD.

An example of Type I SD is the post-roll, or Gillingham Illusion (Ercoline, DeVilbiss, Yauch, and Brown, 2000), which can be summarized by referencing Figure 1.

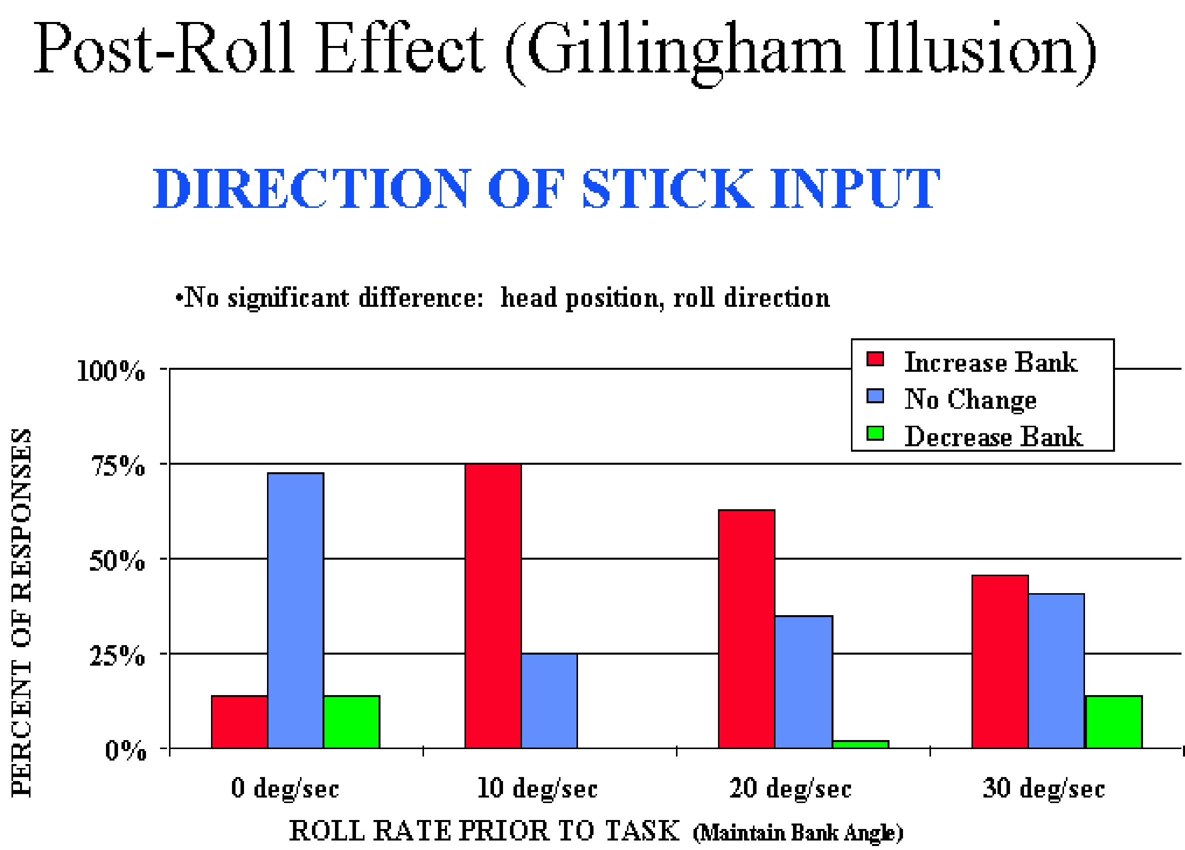

FIGURE 1. Gillingham Illusion Results

Following sustained roll rates of three different magnitudes (four if you consider the null condition as a roll rate), the subject was tasked to maintain the last perceived bank angle. The rates of roll tested were at 10 degrees/sec, 20 degrees/sec, and 30 degrees/sec. There was found a significant difference between the null roll condition and the three different roll rate responses. It was also found that each roll condition, upon stopping, generated a roll sensation contrary to the direction of the initial roll. For example, if the direction of roll was clockwise, then the sensation perceived by the pilot was counterclockwise, and generated stick inputs that resulted in a clockwise aircraft movement.

Type II SD can be demonstrated by considering the Graveyard Spin (Gillingham and Previc, 1993).

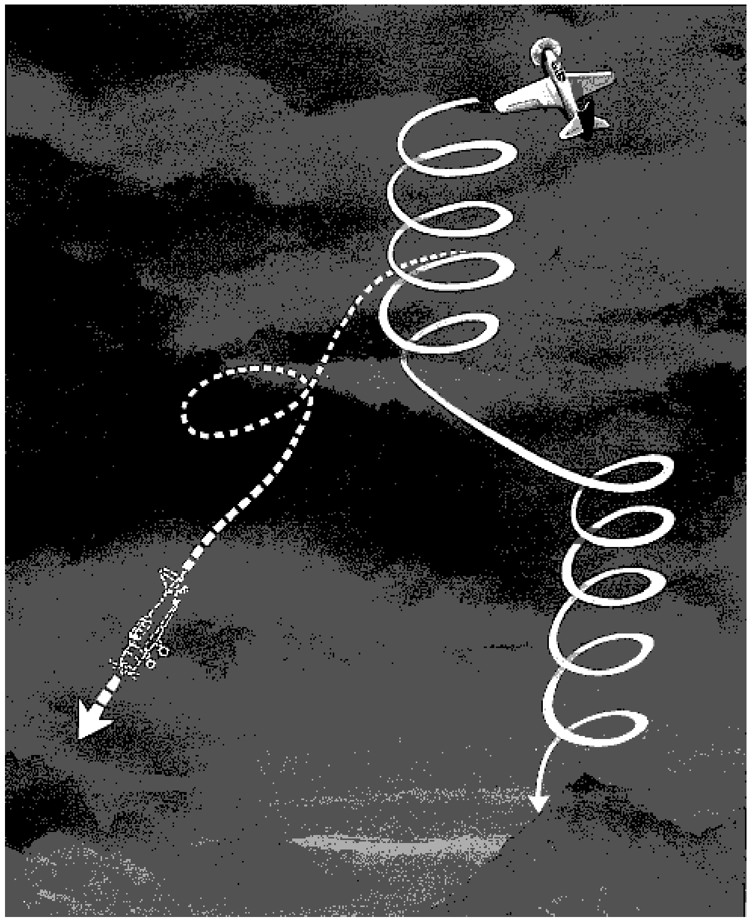

FIGURE 2. Graveyard Spin

In the case of the Graveyard Spin, the pilot enters a spin and stabilizes in yaw (also dampening out the inner ear sensation of rotation). Once control inputs are applied to stop the spin, as the aircraft begins to decrease its angular rotation, the result is a sensation of the aircraft beginning to spin in the opposite direction. When this occurs, and the pilot looks at the aircraft turn needle or compass card, a conflict is now generated between the opposite yaw sensation of the inner ear (erroneous) and the actual yaw displayed by the flight instrument. The pilot must now decide which system to believe—inner ear or eyes. It is a recognized conflict. An important distinction to remember when looking at Type II disorientation is that the individual may not actually recognize at first that they are experiencing disorientation (often the first reaction is to suspect instrument malfunction and "tap" on the instrument case), only that there is a discrepancy between what their internal orientation senses are telling them and what the aircraft instruments are displaying. If resolved properly the pilot will ignore the inner ear sensation of yaw in the incorrect direction and apply controls necessary to arrest the spin.

Type III SD, or incapacitating disorientation can be illustrated by considering the following anecdotal descriptions of the Giant Hand Illusion. Names are withheld at the request of the pilots. The first is a description of a situation that occurred to a T-38 Instructor Pilot:

> "It started routinely. The student and I were coming home on the wing for an instrument approach to cap off a two-ship formation flight that was pretty uneventful. There were layered decks and we were in and out of the tops of a lower deck while getting vectored home. I decided to fly into the actual weather, since I was pretty sure the student was about cooked from the prior descents and I needed some IMC [Instrument Meteorological Conditions] time.
>
> Lead started to go left and descend for the base turn and I followed. Okay, I **tried** to follow. The miserable T-38 was acting up and would not go left. No amount of force, cursing, or pleading would make that baby go left. Lead was kind enough to hold up for me, after I told him to roll out, and I continued to keep my eyes outside to remain visual.
>
> I asked my student to turn the bird left, and together, it worked fine. That crisis passed, I tried to close the gap and discovered the flight control problem was back. I could move the stick up, down, right, but not left. I put all my weight into it, but could not move the stick. I passed controls to the student and he had no problem making it go where he wanted. After a few moments inside with assorted checklists and in-flight guides, I tried one last time before saying the dreaded "E" word and lo and behold: success. Like any good pilot, we flew home, wrote it up and got a big fat CND [Can Not Duplicate], with no FO [Foreign Object] found."

The second incident occurred to a F-16 pilot:

> Visual conditions: clear night, no visible horizon, random stars and ground lights mixed together—difficult to tell the sky form the ground.
>
> "I was number two of a two ship formation flight, lead was already in a turn and I was beginning to move into position. I could not see lead's aircraft, but I could see three of lead's aircraft lights. I was trying to bank my aircraft to move into position. The aircraft would not respond. The harder I tried to push on the stick, the more resistance I felt in my arm. I was trying to bank, but the aircraft seemed like it was too heavy or it just would not bank. I felt as if I was frozen in a roll. I had to stop the rejoin until I could get control of the aircraft by trying to fly instruments. After a short while the aircraft responded to my inputs."

Type III SD is not understood completely. In flight research is probably necessary to duplicate some of these conditions.

CAUSES OF SD

A vast amount of time and effort has gone into understanding the specific causes of SD at the mechanism level, but much of that complex discussion is beyond the scope of this paper. However, in fairly simple terms, it can be asserted that discrepancies between and among the visual, vestibular, somatosensory, and cognitive systems **can** lead to a mismatch between the perceived orientation and the actual orientation. Various contributing factors include attentional anomalies, experience level, expectations, and interpretation of inputs.

It must be noted that simply because this mismatch exists does not automatically necessitate the occurrence of an SD incident. Quite often, the individual crewmember is aware of the mismatch and chooses, either consciously or unconsciously, to disregard the orientation inputs from his or her internal orientation systems and to focus and rely on the orientation inputs from the aircraft instrumentation. SD incidents occur when the crewmember is either unaware of the mismatch, or aware of the mismatch, but unable to reconcile the cause, or unable to overcome the internal sensory signals and rely on the external orientation information that derives from the aircraft instrumentation.

Much has been written lately about the significant problems associated with the loss of situation awareness (LSA). Because of this attention, a significant amount of resources has been applied to its research to produce a better understand of its consequences. Spatial disorientation (SD) is a large part of situation awareness (SA). Figure 3 illustrates the relationship of spatial orientation (SO) to SA. Another way to look at this relationship is to consider SD a large part of LSA. When one loses SO, they have lost SA. When one losses SA, they have not necessarily lost SO.

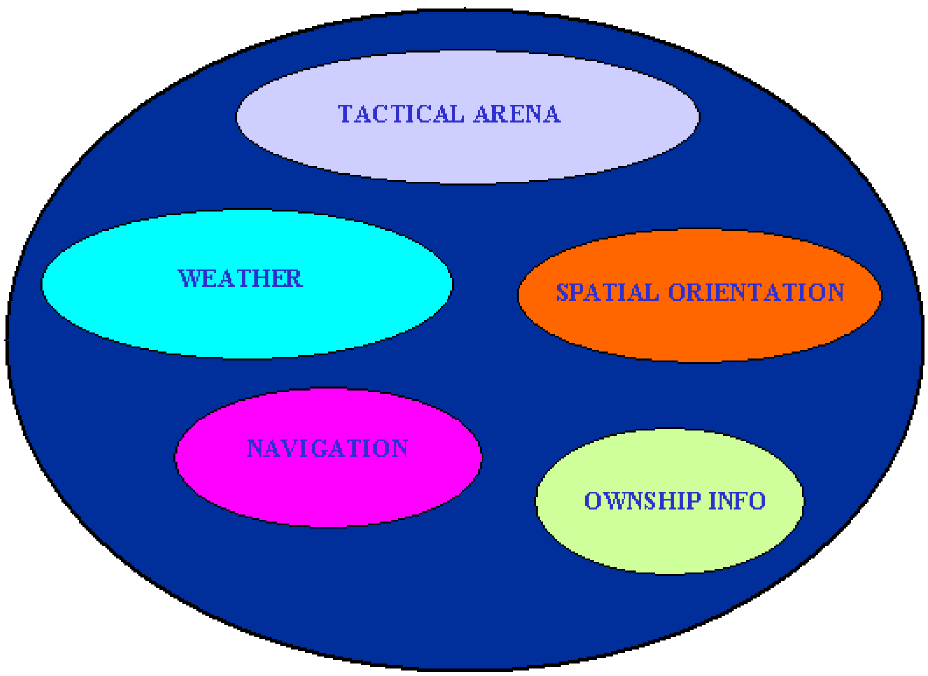

FIGURE 3. Components of Situational Awareness

CONSEQUENCES OF SD TO THE USAF

The consequences of SD can be discussed in many ways, but the economic approach may be the most telling. A standard used for many years is the rate at which a mishap occurs every 100,000 hours of flying time. If at any time during this 100,000 hours of flight, an aircraft is destroyed, a life lost, or more than $1M USD would be required to repair the aircraft, the aircraft accident is called a Class A mishap. Figure 4 shows the Class A mishap rates for the USAF for the period of 1972 to 2000.

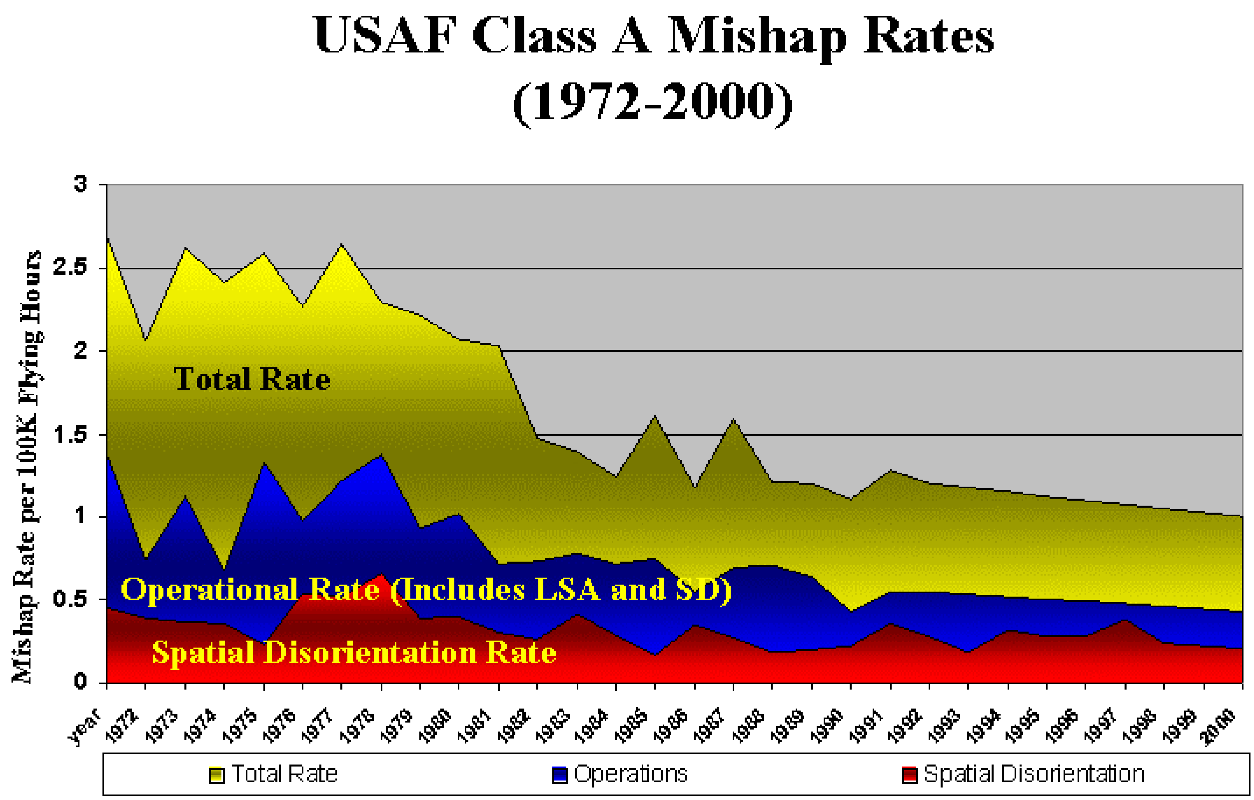

FIGURE 4. Class A Mishap Rates (1972-2000)

As can be seen, the total Class A mishap rate per 100,000 flying hours has been reduced significantly over the past 30 years. Nevertheless, the rate of Class A mishaps due to SD has remained relatively constant when averaged over the 30 year period. Unfortunately, an important item not shown in this figure is the average cost of these accidents over this same time period. Because of the increasing cost per individual aircraft, the actual monetary values have increased. For example, for the period from 1990 to 1999, approximately $557M US dollars worth of aircraft were lost due to SD. As well, and certainly more importantly, 44 crewmembers were killed during this time period. One fact that can be accepted by all, with no disagreement, is that these costs will only increase with the future generations of aircraft. These losses represent a significant drain on the resources of the USAF.

US AIR FORCE RESEARCH LABORATORY'S (AFRL) SD COUNTERMEASURES (SDCM) PROGRAM

In an effort to reduce the SD mishap rate by about 50% within the next 5 years, AFRL initiated a five-year program with a three-pronged approach: training, displays/technologies, and orientation mechanisms research (Heinle, 2000). The intent of the program is to coordinate the multiple and varied research avenues into a coherent research program that will reduce, and eventually eliminate SD as a significant factor in USAF aviation mishaps.

The training research is attempting to develop a metric for the measurement of SD training effectiveness, as well as developing ground and flight based scenarios that will expose aircrew to conditions in which SD is likely to occur. In this way, individuals will be more aware of what SD "feels" like and therefore be more likely to recognize it when it occurs in an operational setting. This will, in effect, allow us to reduce the number of Type I SD accidents while producing more Type II SD incidents, i.e. situations the pilot can recognize and apply training techniques to prevent from developing into a Class A accident. In addition, the Lab has established the only website dedicated specifically to the reduction and elimination of SD in the world. This public site is designed to be useful for researcher and operator, military and civilian, and is a very useful tool for anyone involved in SD. It can be accessed at www.spatiald.wpafb.af.mil.

The displays and technologies portion of the program is in the process of developing novel and more intuitive methods of presenting orientation information to the aircrew. Here, the projects range from Pathway in the Sky, an integrated alternative symbology set for use as a primary flight reference, through improvements to Helmet Mounted Display symbology and the use of Night Vision Devices, to the integration of visual, auditory, and tactile information into a single orientation suite. All of this research will eventually assist the aircrew in preventing the sensory mismatch that can initiate an SD event, thereby eliminating the Class A SD-related mishap.

Mechanism research has been a classic approach to a solution of the SD dilemma, and it continues to play a significant role in the current research program. Because, however, this type of work generally delivers results after many years, and this is currently a five-year program, therefore the work must focus on immediate issues like the understanding of the Giant Hand phenomenon. An understanding here will go far in complementing and further expanding previously completed mechanism research. The program will rely heavily on collaborative efforts with allies like those at this conference, and basic research funding organizations like the USA's DARPA/DSO and the USAF's Office of Scientific Research.

ROADMAP FOR THE FUTURE

The problem of SD has been intertwined with aviation since the beginnings of manned flight, and only a concerted and coordinated effort will have any impact of significance. The US AFRL SDCM program has concentrated on two primary aspects of the SD issue: discovery/development of a metric to measure SD and the development of tools and techniques useful to aircrew in the very near term. In this way, pilots can improve their life expectancy now, not at some unspecified future date in a soon-to-be fielded aircraft.

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A SD-Demonstration Program for German Navy Tornado Aircrew, First Results

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Summary: Based on a class 1 aircraft accident of the German Navy in 1997 and a class 1 mishap of the German Air Force in 1998 with the loss of all 4 crewmembers, Division III of the GAF Institute of Aviation Medicine installed a program for Tornado aircrew to demonstrate various SD situations in the Flight Orientation Trainer. Although during these accidents every possible flight information was available to the aircrew, the situation was not perceived as disorienting and dangerous but the focus stayed on the primary task intended or wrong priority chosen.

Spatial disorientation, namely the loss of situation awareness, is one of the main factors and by far too often a contributing factor responsible for a/c accidents. But spatial disorientation is one of the main causes of accidents not only in modern, super-agile fighter aircraft; this is also true for older designs of jets and all other types of aircraft.
The last 15 to 20 years have seen dramatic developments in technology with an enormous impact on aircraft design and performance. Air Forces of many nations are introducing fighter aircraft of the fourth generation; the design of fifth generation fighter aircraft is already on the drawing boards.
Compared to today's fascinating technological possibilities of modern aircraft design, the evolution of the human being with its old-fashioned sensory apparatus is not really up to date.
The gap between the sensoric, motoric and general physiological capacities of man and modern technical capabilities is increasing in such a way as to make it impossible for the human body to keep up with or even master them.
Spatial disorientation is a killer. Almost all aircrews experience spatial disorientation during their career one time/way or another. All aircrews accept the potential dangers of SD but few of them perceive this danger as immanent and potentially dangerous in every flight. During flight briefings this fact is mentioned but all to often neglected or not given enough attention.
With the introduction of the Flight Orientation Trainer, FOT, the German Air Force acquired a tool to demonstrate and teach aircrews about the treacherous dangers of spatial disorientation in the flight environment. The Flight Orientation Trainer (Gyrolab 2000, ETC) was installed in Div. III, German Air Force Institute of Aviation Medicine in 1994. Over the years various scientific studies and research programs have been carried through with the FOT. In 1999 a test trial with German Naval Aviators took place and led to the SD Demonstration Program performed on a regular basis in 2000. More than 50 Navy pilots took part in the program.

The concept of use for the FOT had been decreed by the Surgeon General, GAF, in February 2000. It focusses on six major issues:

1. Demonstration of spatial disorientation for aircrew
2. Research
3. Development of demonstration profiles
4. Anti Airsickness Trainings Program (AATP)
5. Flight surgeon related problems
6. Aircraft mishap investigation – if requested

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

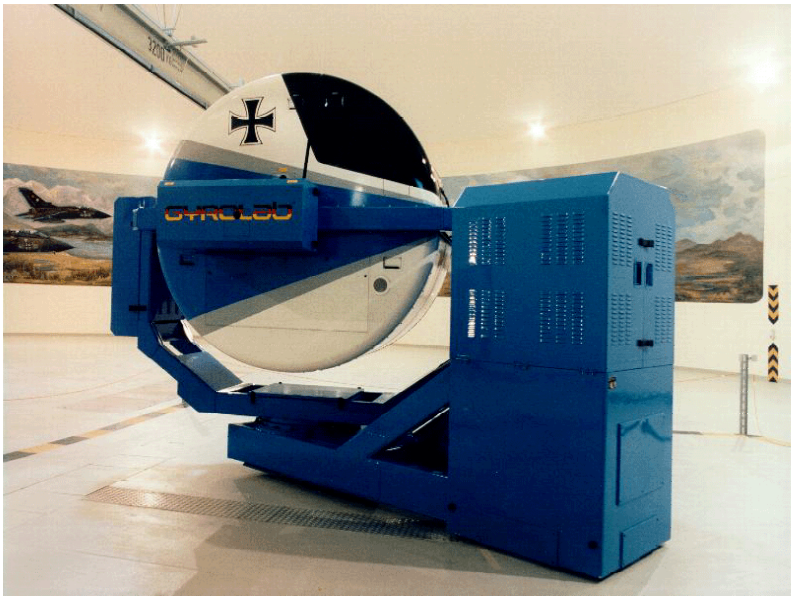

Figure 1: Flight Orientation Trainer (FOT)

The FOT generates vestibular and visual illusions.
The system can rotate 360° around all three spatial axes without any stop. In addition, a load factor of 2.2 G can be achieved using the planetary arm, similar to a centrifuge.
Planetary arm movements combined with simultaneous rotation around the vertical axis is used to simulate linear accelerations. Control authority can be transferred from the master console to the gondola and back. The device itself consists of two main components - the master control console (MCC) and the gondola assembly. The master control console is the heart and soul of the Flight Orientation Trainer. Here FOT rides are controlled, and profiles, movements and display modes are designed and generated. The cockpit of the FOT gondola resembles a virtual twin-jet aircraft.
Light cannons project the display of the virtual flight environment onto a concave mirror with the dimensions of 120 x 40°.

The system provides for two different databases concerning the virtual environment.
The pilot sitting in the gondola is continuously monitored by two cameras, one of them active in the infrared spectrum to guarantee that the pilot can be monitored even in a completely dark cockpit. Furthermore, the pilot's actions and maneuvers can be taped on video.

Continuous communication with the personnel at the master control console is maintained via headset.
In 1998, initiated by the Senior German Naval Flight Surgeon in cooperation with the office of the General of Flight Safety and the German Air Force Institute of Aviation Medicine, we established a program for jet aircrews to again emphazise the dangers of spatial disorientation. Unfortunately, a tragic accident in the North Sea led to the starting point of the program. A German Tornado of a Naval Air Wing crashed into the sea, most probably because of technical problems. The time between when the problem occurred and the actual impact was approximately 30 seconds. The crew responded immediately to save the aircraft and continued their efforts right until the time of impact. There was no apparent attempt of the crew to eject.

The FOT program is designed to refresh the crews' memory of what they learned during the initial training to demonstrate that even extensive experience does not prevent a crew from becoming disoriented and that in hazardous situations the obvious and rational is often pushed aside by habit patterns that have become ingrained in the subconscious over the years.

The program's main objectives are to make the pilot recognize his/her own deficiencies like
- Spatial Disorientation
- Capacity to perform properly
- Situational Awareness
- Perceptual conflicts
- False assumption of safety

It consists of a variety of profiles, both passive and active, to put the pilot in the loop. Standard profiles designed to refresh the crew's awareness of basic problems are combined with situations from real aircraft accidents to demonstrate that time is precious, task prioritization essential and decision-making absolutely critical.

The program is designed to:

- Improve the aircrew's judgment on situations which are likely to cause SD
- Determine priorities as to the flight attitude
- Recognize discrepancies between sensory perception and instrument readout
- Perform compensatory actions in the FOT during the SD profiles

Before entering the SD program the pilots received an in-briefing about the FOT, the different profiles and emergency procedures. After the program everybody had to fill in a questionnaire about the training. They were asked to rate the profiles as to quality and potential benefit as well as to give their opinion about the time frame for a refresher course.

In the table below the different profiles used in the program are listed.

Jet:	Heli:	Transp.:
- GYSPIN	- GYSPIN	- GYSPIN
- GYSPIN1	- GYSPIN1	- GYSPIN1
- EF15	- LEANS	- LEANS
- TOMSPIN	- DRKTKOFF	- DRKTKOFF
- DRKTKOFF	- FSUBYAW	- FSUBYAW

Table 1: Standard profiles for SD-training

The profiles represent the typical illusions and sensations experienced in flight by almost everybody.

The graveyard spin is being demonstrated passively (GYSPIN). During the second run (GYSPIN 1) the pilot in the FOT has the authority over the controls to compensate for the perceived motion. By showing the pilot his "overcompensation" it is possible to make him recover just by relying on the instruments, if the situation permits him to do so. The magnitude of the mismatch between perceived motion and real motion is generally very surprising. The "EF15" profile combines a counterclockwise angular acceleration on the FOT‘s planetary arm and simultanously a rolling motion to the left followed by an abrupt rolling to the left. That simulates the Weapon System Officer in the rear cockpit working his radar while the pilot starts maneuvering without informing his crewmember. After the right-rolling motion the authority is transferred to the pilot in the gondola, and he/she is to recover to straight and level flight. The majority of test persons has problems recovering the FOT. Pilots seem to perform better than the WSOs.

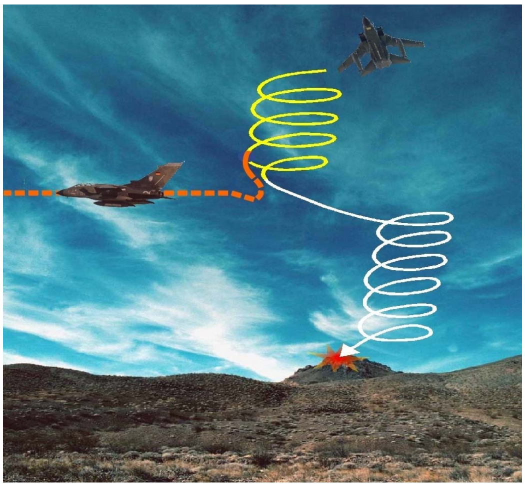

Figure 2: TOMSPIN flight accident profile

The "TOMSPIN" profile is a profile that was designed after a mishap in which an aircraft departed from controlled flight and was lost in a spin. In this scenario the pilot in the gondola is flown into that situation and asked to recover the aircraft using the appropriate **Boldface** procedure. This profile generated a wide variety of reactions from the pilots and WSOs. The range of reactions spanned from the immediate and correct response with the timely decision to eject from the aircraft to a total failure to perform the necessary Boldface procedures until impacting the ground. One pilot mixed up the recovery procedures of three different aircraft he had flown during his career.

The dark takeoff profile (DRKTKOFF) is well known as to its basics. During takeoff acceleration and level-off the pilot perceives a strong climbing attitude and pushes the stick forward to compensate, initiating an involuntary descent. In the FOT all pilots pushed on the stick after authority transfer, initiating a descent with a nose-low attitude ranging from 5 to 30 degrees.

Time permitting, the classic profiles "LEANS" and "FSUBYAW" (simulating a subthreshold yawing motion) were also used.

Table 2 combines the results of 'profile rating' and 'most beneficial profile', as indicated by the participants.

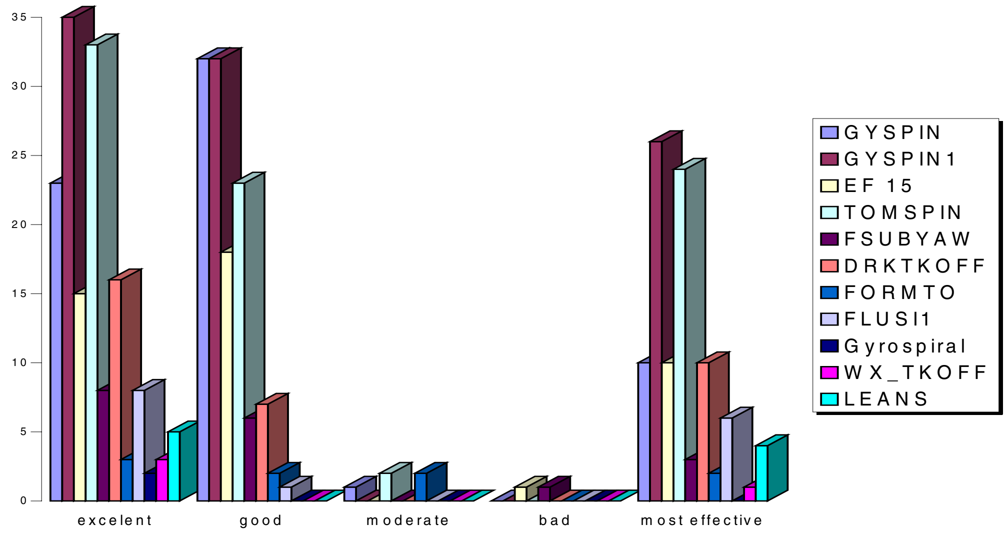

Table 2: profile rating by participating aircrew

The results of the survey clearly indicates that SD training is considered beneficial by the aircrews.
We were able to demonstrate to most of the participating aircrews that even long experience is no protection against spatial disorientation. Astonishment about their own reactions caused most participating pilots to reconsider their approach to SD. This was their clear message from the debriefing after the program to us. An additional indication is the statement of the participants that the training should be repeated every 3 to 4 years.

The objectives of the program have been achieved. The participating aircrews left the program with a heightened awareness of the SD problem, recognizing it both as an important factor affecting their performance and as a big safety hazard. Especially the flight accident profiles which related to their daily work had the biggest impact on the aircrews.
By implementing a well-accepted SD training program consisting of academic and practical instruction – in a demonstrator/ simulator or even better in the air – we have a good chance of reducing SD as a major lethal factor in aviation. We need to find a way to make every aircrew consider SD always and everywhere. Otherwise SD will continue to be a killer in the first degree.

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Spatial Disorientation Demonstration in The Netherlands

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SUMMARY

In this paper we give an outline of the ground course on spatial disorientation that TNO Human Factor provides for military student aviators of the Royal Netherlands Airforce. During this one-day course a variety of laboratory equipment is used to let students experience and understand different disorienting phenomena and to make them aware of the peculiarities and limits of their sensory systems. With these demonstrations students learn in what situations disorientation, and possibly also symptoms of motion sickness, can be expected and when not. The course also includes an introductory session on the consequences of night vision for situational awareness, which we will describe here. We pay special attention to the motivation and form of the course. Finally we briefly discuss how the flight simulated demonstrator (DISO) of the RNLAF will be employed for demonstrating some flight-related visual illusions and how we upgraded the cockpit with night vision compatibility for practising the use of night vision goggles (NVG).

INTRODUCTION

In the early '90s, the Royal Netherlands Airforce (RNLAF) formulated a master plan to countermeasure spatial disorientation (SD) as a cause for flight accidents. Until then, some general theory on SD problems was presented in the Aviation Physiology class, but there was no actual familiarisation program. The RNLAF asked the Equilibrium & Orientation group of TNO Human Factors in Soesterberg to organise a program for demonstrating SD phenomena using their vestibular research facilities. This was to be realised on a short term. The goal was to have a ground course at the beginning of the elementary flying training in which student pilots would learn the limits of their sensory systems and the dangers of disorientation. On a longer term, the RNLAF asked to develop an advanced course with exercises for the more experienced pilots ("refresher course") in which the pilot practices his priorities during man-in-the-loop scenario's.

The advanced course does not exist yet, although with the development of the Desdemona concept our thoughts begin to crystallise. In the present paper we will give an outline of the basic demonstration program, designated "Demo Basic", which started in 1994 (De Graaf et al. 2000). Since then, more than 300 student aviators participated. Students invariably evaluate the course as very informative and useful. We will describe both the form and its contents, and will identify the – to our opinion – essential elements. At the end of this paper we will describe how we the Demo Basic can be extended with the flight simulated SD demonstrator of the RNLAF (DISO). Recently we investigated the added value of this device, and this year we will incorporate the DISO into a new edition of the Demo Basic.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

OUR APPROACH

Currently, about 65-70 student aviators are being trained on Woensdrecht AFB each year, future pilots on fixed-wing and rotary-wing platforms still together. Each of them participates in the Demo Basic after preferably 10-15 hours of flying experience. Students attend the course in small groups of three persons at a time. This allows for an open, interactive atmosphere with sufficient room for questions and discussion. More importantly, still, the small groups make it possible for each student to experience the demonstration him- or herself, and also to observe the stimulus and the response of their fellow students. This way they realise that, despite some inter-individual difference, their sensory systems show comparable idiosyncrasies that cause disorientation.

It is considered very important that students observe their own reactions ("from the inside out") and compare these with what they see and hear from their colleagues as a bystander ("from the outside in").

Furthermore, we believe that – for familiarisation purposes – demonstrations should be straightforward and understandable. What actually happens should be clear and unambiguous. The student will find it hard enough to match his or her sensation with what he observes that is going on. For this reason, we strongly recommend not to incorporate too complex situations and especially not to use so-called "cheated illusions". Although cheated illusions may give students some idea of how certain disorienting sensations feel, they are produced in a "faked" way and do not make clear the mechanism that causes the illusion. For example, one can "suggest" a tilt sensation during a dark takeoff by actually tilting the device (see Figure 1), but for observant students this is rather trivial. We therefore believe that the use of correct stimuli gives students true understanding of the disorienting mechanisms, which is to be preferred over the mere demonstration of a variety of sensations that may occur during certain manoeuvres.

Illusions should be demonstrated by the same mechanisms as occur in-flight.

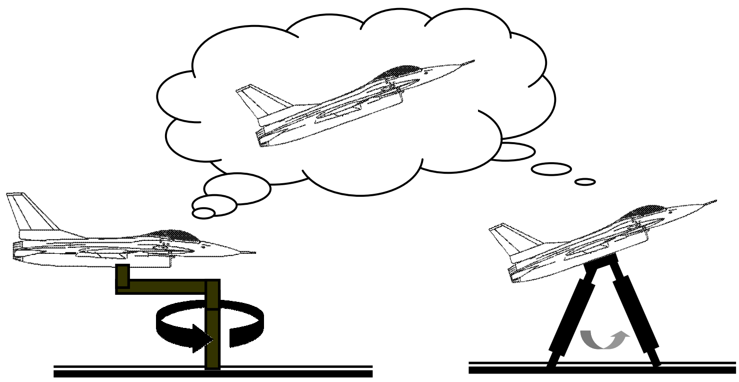

Fig. 1 Demonstration of pitch-up sensation (eg. during a dark takeoff) with a "true" illusion (left), or with a "cheated" illusion by actually tilting the device

In this respect, one does not necessarily require a high-tech demonstrator device with a realistic cockpit, since the fundamentals of SD phenomena can be adequately demonstrated using research facilities of a vestibular laboratory (see also AGARD-625)

DEMO BASIC CONTENTS

The Demo Basic is a one-day course and takes place at TNO-HF. The course includes the following topics:

- Basic theory on SD and physiology
- Demonstrations of (mainly vestibular) illusions
- Night Vision

Theory

During a 45 minutes introduction at the beginning of the day some basic physiology is reviewed. Since the students already followed a tutorial on aviation physiology earlier in their education, we can focus on the sensory systems and their characteristics tailored to the demonstrations later that day: the visual and vestibular system and the somatosensory system. The optimal operational range of each sensory system is explained as well as the close interaction between them. It is made clear how the sensory systems malfunction in transport situations. At this point it is stated that in each transport situation a person is, *by definition*, type 1 disoriented, and that one has to use his mind to interpret the situation, for example by using his instruments. It is stressed that SD is a creeping killer, which may emerge when one is the least expecting it. An anecdote is told of a SD incident, in which a pilot suffered from a persistent (visually induced) inversion illusion. This anecdote should strike students with disbelief first, and should become more acceptable throughout the course when they experience several persistent illusions themselves.

Demonstrations

The emphasis of the Demo Basic is on demonstrating the elementary disorientation effects, mostly related to the vestibular system. The organisation of the course is such that it starts with the most simple illusions and builds up to the more complex and sensational ones. In this paper, however, the presentation of elements is ordered according to the various pieces of equipment. Understandably, in our laboratory this mainly consists of vestibular devices. We do have some possibilities to induce visual illusions, be it with rather abstract stimuli that are not directly related to flight (e.g. random dot patterns). Still, the sensations induced by these displays are quite solid and useful to illustrate some basic visual-vestibular interactions. We have planned to extend the course with more flight-related visual illusions in the DISO cockpit (see later).

3-D rotating chair, yaw mode

The demonstrations start with a session in our servo-controlled 3-D rotating chair (Figure 2). The response of the horizontal semicircular canals is experienced during rotation on a vertical yaw axis. We use a velocity step of 90°/s that is sustained for 90s, while a hooded aviator verbally reports the perceived angular motion and also indicates the change in position in time by pointing a joystick in a fixed heading (like a compass needle).

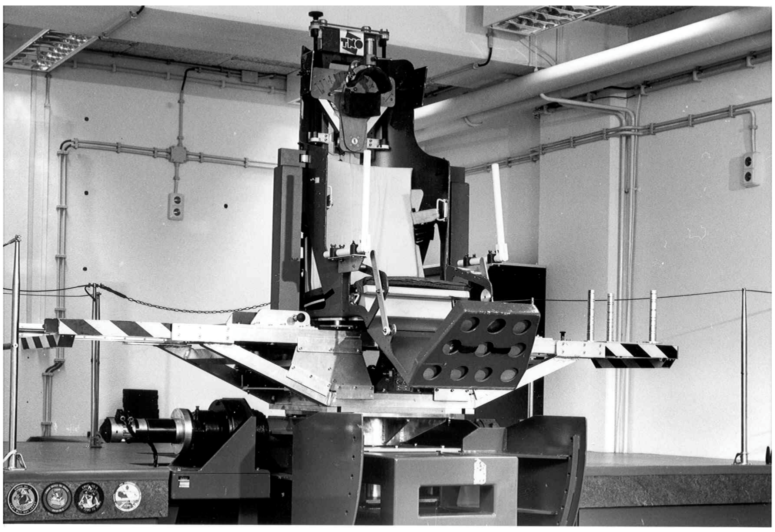

Fig. 2 The 3-D rotating chair in normal yaw mode (rotating on vertcial yaw axis). Demonstration of somagyral effect and the adverse effects of nystagmus on reading.

For the two student aviators watching along the sideline this clearly shows that the turning sensation fades away (somatogyral effect) during constant velocity and starts again, but now in the opposite direction, when the chair stops. It is explained that this concerns type 1 disorientation. After the first student has experienced this sensation successfully, the other two take turns. If a subject student is confused or does not exactly experience the intended sensation (for instance because (s)he has difficulties in ignoring the airflow that results from rotation), the instructions are explained again and it is given another try until it does work out. The time schedule of the course easily allows for repetitions.

The adverse effects of (horizontal) nystagmus on instrument reading are shown using a sinusoidal acceleration profile with a frequency of 0.033Hz and maximum speed of 180°/s. The hooded student is asked to read a matrix of numbers on a display straight-ahead. Here the relation with the flying situation is made and type 2b disorientation is discussed (one knows to be disoriented, but is unable to overcome it because of incapacitating eye movements).

3-D rotating chair, excentric yaw mode

The somatogravic effect is generated with the 3-D rotating chair positioned at about 0.5m off-centre (see Figure 3). The angular velocity is increased in a stepwise manner from 0-180°/s producing a lateral acceleration of about $0.8 m/s^2$. A dome is mounted on the chair onto which a random dot pattern is projected that rotates on the pilot's roll axis. This demonstrates a nice visual-vestibular interaction. Centrifugation in the dark typically produces a sensation of 30° static outward tilt (somatogravic illusion), whereas the rotating visual pattern on a stationary chair generally gives 15° of illusory body tilt. The combination of centrifugation and visual roll motion, however, effectively produces a sensation of full head-over-heels rotation as in an aileron roll (de Graaf et al. 1998).

This element is considered an essential part of the course because it convincingly shows the aviators that sensations that are completely different from the actual stimulus are easy to obtain. Moreover, comparison of the individual time histories and magnitudes of the response of the three aviators shows that different people may assign different relative weightings to the visual and vestibular signals, but that in general the response is the same.

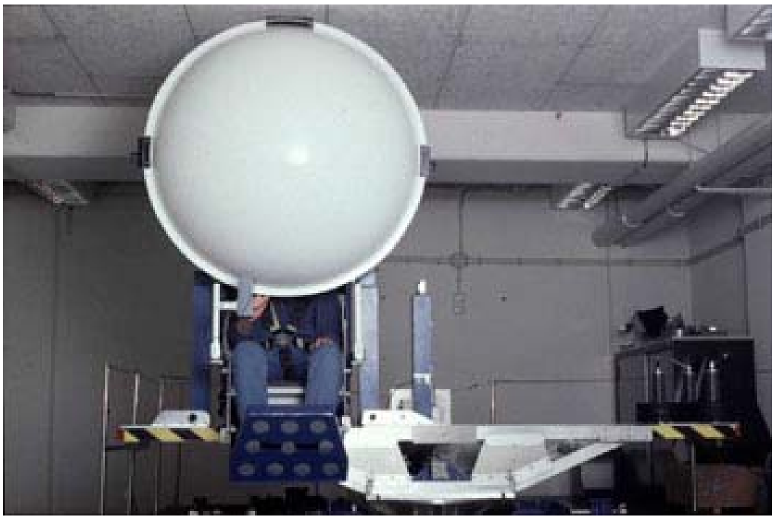

Fig. 3 Excentric mode of 3-D rotating chair. Demonstration of somatogravic effect and interaction with visual stimuli.

<u>3-D rotating chair, roll mode</u>

With the 3-D rotating chair in the roll mode (Figure 4), we demonstrate two effects. First, students estimate the angle of perceived body tilt (attitude) while the chair is put in different static orientations. This shows how people overestimate their body tilt in the dark and how inaccurate the biological attitude indicators are. Typically, in our chair subjects overestimate their tilt angle with a factor two, and it is not uncommon that subjects feel almost inverted at 90° of tilt to one side. The inability to estimate tilt angles correctly is very surprising to the aviators, who are supposed to fly with a precision within degrees. This way they learn that the correct sensor for this precision is outside the body, i.e. the flight instruments. When the chair is positioned upright again after several minutes of body tilt to the same side, there remains a feeling of 5-10° tilt in the opposite direction. This is an example of the "leans".

The second effect demonstrated in this mode is the "ferriswheel illusion" (Mayne 1974). Constant rotation about the horizontal roll axis leads to a series of sensations, where the aviator at the end no longer feels rotation but, instead, an alternating horizontal and vertical translation. This illusion nicely contrasts with the sensation during excentric yaw motion where aviators perceived continuous roll motion during linear acceleration, while during this actual roll motion they perceive linear acceleration. Since this condition is considered quite exciting, we have scheduled it towards the end of the day.

Fig. 4 The 3-D chair in roll mode. Demonstration of leans and ferriswheel illusion.

<u>Barany chair</u>

On our simple rotating chair shown in Figure 5 we demonstrate Coriolis effects. By comparing the effects with eyes open and eyes closed, students experience that angular motion is accurately perceived with a clear view on stable surroundings, but that the sensations may soon become disorienting, or even discomforting, when there is no clear out-the-window view. At this point the causal mechanisms of motion sickness are discussed in more detail, based on our spatial orientation model (Bles et al. 1998). Of course we keep the angular speed during the demonstration low in order to avoid real problems with motion sickness.

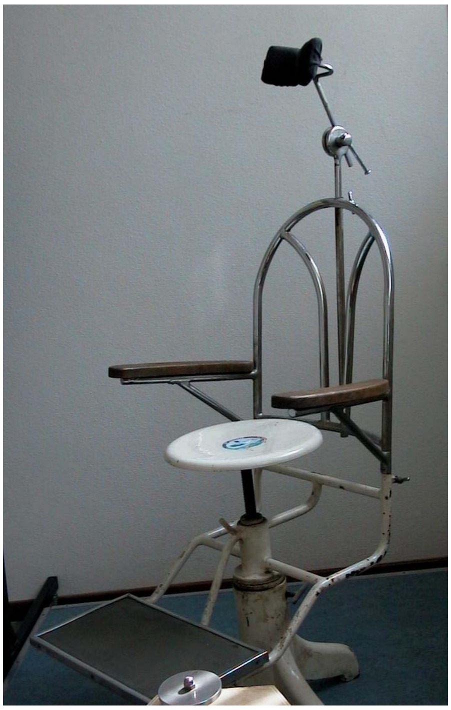

Fig. 5 Classic rotating chair.
Demonstration of Coriolis effects.

<u>Tilting room</u>

In our tilting room (Figure 6) we demonstrate the effect of a tilting visual surround on posture and the percept of verticality (visual leans). One pilot is standing on a fixed platform inside the room, trying to keep upright stance, while the room is tilted statically (10°) or dynamically (frequency < 0.2Hz). The subject verbally reports on the apparent deviation of the subjective vertical. His or her postural behaviour is visualised for the other pilots by displaying the forces measured in the platform under the feet. The message of this exercise is that, despite the fact that you know that you are mislead by the sensory information, it is impossible to choose the correct information. Thus again: depend on your flight instruments.

Fig. 6 TNO Tilting room. Demonstration of visual leans.

Night Vision

The course includes a special block on night vision sensors. Night vision goggles (NVGs) and thermal imagers (FLIR) make it possible to look outside at night, be it in a severely degraded fashion compared to natural vision during the day. The degradation of the visual image makes it more difficult to adequately maintain accurate situational awareness (SA). In a session of one hour, students learn to appreciate the various visual limitations by hands-on experience (Figure 7). Thus, similar to the demonstration of vestibular illusions, great importance is attached to an understandable and interactive demonstration of night vision apparatus.

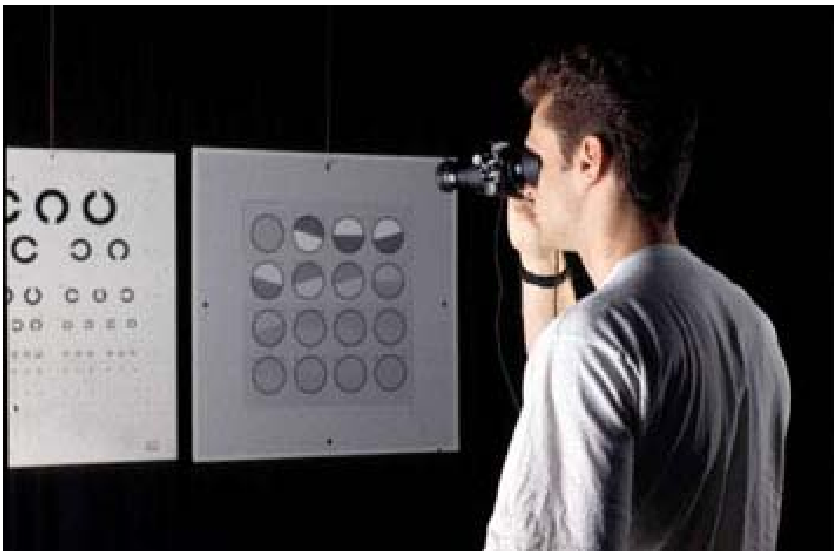

Fig. 7 Demonstration the degradation of vision by the use of NVGs.

The principles of image intensification (night vision goggles, NVGs) and thermal imagers are explained, and their (dis)advantages are compared. The five main visual limitations of NVGs are illustrated with five simple and representative tests mentioned in table I.

Table I The five main limitations of NVGs. The right-most column gives an approximate indication of the difference between day vision and night vision through a NVG.

	limitation	**test**	**"loss factor"**
1	resolution	visual acuity chart	3-5x
2	image contrast	contrast sensitivity chart	4-8x
3	field of view	perimetry	10x
4	ability to read	near-acuity chart	8x
5	colour perception	false colour NVG images	∞

Next it is explained why depth and distance cues are of special importance to SA, and how these cues are degraded, absent or misleading in night vision sensors. The mechanisms of depth perception are reviewed (stereopsis, motion parallax, monocular depth cues), including the concept of visual illusions. The motivation for this exercise is to show students that a good understanding of vision and visual illusions is important because it is possibly the best way to identify false or incomplete visual sensations.

Recently we have upgraded the cockpit of the DISO so that it is night vision friendly. As described in the next section, we will use this feature to extend the night vision training of the Demo Basic with some NVG practice in a cockpit.

SD Demonstrator DISO

Since a few years the RNLAF owns an “Airfox DISO” (AMST Systemtechnik, Austria). This so-called “flight simulated disorientation demonstrator” is located at the neighbouring Aeromedical Institute in Soesterberg (Figure 8), which makes it convenient to combine the device with the Demo Basic. The DISO consists of a generic cockpit with a one-channel collimated out-the-window (OTW) display. The cockpit is mounted on a synergistic motion platform with six degrees-of-freedom (6-DoF). Between the motion base and the cockpit, an extra yaw axis allows for unlimited yaw rotation. The motion characteristics are specified in Table 2.

Fig. 8 SD Demonstrator DISO (AMST Systemtechnik).

Table 2 Specifications of DISO motion platform.

	Displacement	Velocity	Acceleration
Pitch	± 30 º	20 º/s	150 º/s^2
Roll	± 30 º	20 º/s	150 º/s^2
Yaw	± 60 º	20 º/s	150 º/s^2
Additional yaw	360 º	150 º/s	15 º/s^2
Heave	± 0.14 m	0.4 m/s	8 m/s^2
Surge	+0.32/-0.27 m	0.4 m/s	8 m/s^2
Sway	± 0.28 m	0.4 m/s	8 m/s^2

Recently we investigated how the Demo Basic can obtain added value from the DISO. Here we will describe the elements that were selected to be included in the program, in addition to the elements described in the previous sections. Several SD illusions are standard implemented in the DISO (see Table 3, the visual illusions marked with *), although the RNLAF instructor modified the parameters of some of the illusions to make them more convincing and effective. With respect to the elementary vestibular effects (Coriolis, somatogyral, somatogravic, Dark takeoff, etc.) we preferred to continue the demonstration of these effects in our laboratory. As argued above, laboratory equipment allows for more open and observable demonstrations than a cockpit where the student pilot is physically separated from the instructor and colleagues. We therefore had the "luxury" to disregard (most of) the vestibular illusions of the DISO, and to look primarily at the visual illusions and night vision possibilities. Still, it was considered useful to include the "Leans active", which simulates the leans after recovery from a co-ordinated turn. Although the illusion is cheated by disabling roll motion in the direction of the turn, the demonstration may be educational since it allows the students to make a connection between the sensation in the tilting chair with that in the cockpit. For this reason, it is relevant that the DISO session will be schedules at the end of the day after the TNO sessions.

The following *visual illusions* were considered appropriate in the context of the Demo Basic: autokinesis, false horizon, black hole approach, variations of runway perspective, and some illusions created by the DISO instructor, such as cloud leans, and confusing star-ground light (for a description of illusions, see e.g. Benson 1988).

Table 3 List of standard illusions in the DISO.

	Illusion
1	Coriolis (Barany chair)
2	Nystagmus
3	Oculogyral
4	Autokinese*
5	Somatogyral
6	Coriolis active
7	Graveyard spin
8	Leans (active)
9	Leans (turbulence)
10	Blackhole approach*
11	Dark take off
12	False horizon*
13	Variation of runway width*
14	Variation of runway slope*

With respect to the *night vision capabilities* of the DISO, we concluded that with minor modifications the cockpit could be made "NVG compatible", or perhaps more correctly "NVG friendly". The collimating display of the DISO is sufficiently uniform to allow for the use of F4949 NVGs. This is relevant, since the depth of focus of NVGs is only about 0.04 diopters (compared to 0.15 diopters of the eye), and optical aberrations would easily lead to blurred parts of the image. Thus the collimator's optical quality itself is suitable for the use NVGs. Ideally, a NVG compatible cockpit should meet the following requirements:

1. Canopy reflections due to instrument and cockpit lighting should be eliminated
2. OTW display should be invisible for the unaided eye
3. OTW display should give realistic NVG images

Regarding the first point, instrument reflections are normally eliminated by filters that let through visible light (400-600nm) but that block the (near) infrared part of the spectrum (600-1000nm). Instead of placing filters in front of each instrument, however, we opted for a less expensive solution and placed 2ND (neutral density) filters in front of the NVGs' lenses (Figure 9). These filters attenuate the available light (both visible and infrared) by a factor 100. The F4949 NVGs used by the RNLAF contain an ANVIS class-b filter that already blocks the visible part of the spectrum, so that the net effect of our filters is to attenuate the (near) infrared part of the spectrum. This seems adequate to make the instruments indiscernible through the NVGs, while the OTW display is sufficiently bright to remain visible through the NVGs. In fact, seen through NVGs with a 2ND filter the OTW image has the appearance of a night scene without moonlight. Using a 3ND (factor 1000) the OTW looks like a moonlit night scene. Because of its brightness, however, the OTW is also visible for the unaided eye looking under the NVGs. Thus, to meet the second requirement mentioned above, we placed a gelatinous filter in front of the OTW display, reducing the visible light with a factor 1000. The combination of both filter types (2ND and gelatinous) results in an OTW image that is dark for the unaided eye but clearly visible through NVGs, and instruments that do not disturb the NVGs image but that can be inspected under the NVGs with the unaided eye.

Regarding the third requirement, a NVG compatible simulator should contain a special “night visual database”, so that the image generator can render the contrast and colours that are typical for NVGs images. However, at this moment, no such night database exists for the DISO. As a result no meteorological or geographical effects can be shown yet.

Fig. 9 F4949 night vision goggles with 2ND filters. In combination with the gelatinous filter in front of the collimated display, the NVGs can be used for training in the DISO.

With our simple modifications, the DISO can already be used for some elementary NVG training:

- Adjusting and focusing NVGs
- Showing the consequences of NVG compatibility (with and without filters), for instance the need to alternate gaze direction between straight-ahead (OTW) and under NVG (instruments)
- Compare the differences between moonlight and starlight conditions (2ND and 3ND filter) and the effect of “speckle noise”
- Getting used to the altered centre of gravity of the head

The following aspects can not be demonstrated yet, but they will become possible with an upgrade of the DISO’s visual database into a night vision database:

- Halos resulting from bright light sources
- Contrast ratios due to the different spectral sensitivity of NVGs
- Visual illusions resulting from meteorological and geographic effects
- HUD (currently, the HUD does not stand out against the background OTW scene as it should, since it is simulated as part of the OTW image. The visual database should be changed as to take this into account).

Due to the small field-of-view of the OTW display, it is principally impossible to train adequate scanning behaviour that helps to update one's situational awareness. Moreover, the spatial resolution of the DISO image is not sufficient to demonstrate the deteriorating effects of NVGs on contrast and resolution. Therefore, demonstration of these principles in the laboratory will still be useful.

CONCLUSIONS

The Demo Basic is a familiarisation program for all student pilots of the RNLAF at the beginning of their flying training. The course is highly appreciated by its participants. It is considered very important that demonstrations take place on laboratory devices, which provide the best way to impart fundamental insight to the students about the mechanisms of disorientation and the limitations of night vision sensors. The unambiguous and "open" stimulus apparatus allows for close interaction between the subject pilot on the one hand, and the instructor and other pilots on the other hand. The basic course will be extended with some flight-related demonstrations in the disorientation demonstrator DISO of the RNLAF. Some typical visual illusions will be illustrated, and we will practice the use of NVGs. For this purpose the cockpit was made NVG compatible. However, the demonstration of basic vestibular illusions will not be done in the DISO, as long as the vestibular laboratory is an alternative.

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Spatial Disorientation Experiments and Training in Polish Air Force Institute of Aviation Medicine

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SUMMARY

Spatial disorientation (SD) is a long recognised problem in aviation environment. During flight the spatial disorientation may appear as a result of inadequate perception of the position or attitude of an aircraft in comparison of the co-ordinate system constituted by the Earth surface. It is extremely difficult to say how often spatial disorientation became the reason of military aircraft accidents [6] but in Poland it is calculated at around 8%. There is no ultimate cure for spatial disorientation; the two ways considered most important are pilot training and extensive research leading to better understanding of nature of SD which is little known despite of about forty years of worldwide awareness about this problem. Probably every air force in the world has its own methods for SD prevention and training programme. We think that most comprehensive approach to this question is introduction of wide training program using all available equipment and conducting of further experiments increasing our knowledge about this very complex problem.

In 1998 PAFIAM went out with initiative of conducting the initial course and training counteracting spatial disorientation with polish military pilots using three simulators.

The full – mission flight simulator "Japetus" is the first element of this system of devices to work on spatial disorientation prevention.

Another device is lately obtained Gyro – IPT spatial disorientation simulator, which's main purpose in contrary to "Japetus" is use in spatial orientation demonstration and training. Both previously mentioned devices are lacking of important possibility in terms of presentation of influence of linear acceleration on pilot's vestibular system. To make possibilities of presentation and training more comprehensive we decided to include human carrying centrifuge into spatial disorientation programme.

SD EXPERIMENTS ON "JAPETUS" FLIGHT SIMULATOR

Problem of spatial disorientation is widely recognized as one of the most serious reasons of flight accidents. In this part we would like to describe some procedures developed at the Polish Air Force Institute of Aviation Medicine with use of flight simulator "Japetus" to counteract the phenomenon of spatial disorientation including situational awareness and visual illusions. We refer to the possibility of standard flight simulator use for investigation the spatial disorientation and training embracing that phenomenon.

Disorientation can be understood as a pilot reaction during the flight when he is forced to focus his attention on difficult meteorological conditions or the other part of the task, which don't allow him to control the whole flight situation. Pilots have to concentrate on different aspect of flight situation, i.e. speed, altitude, performed mission that make them more susceptible to spatial disorientation especially in terms of conscious processing. It may be the background of unaware disorientation (disorientation of type I). The pilot's flight performance in such a case is compromised because of perceptual misinformation. What is important pilot may fly unaware of his disorientation until it is too late for corrective action.

Two kinds of experimental flights on the flight simulator were performed: flights in IFR and in VFR conditions. The flight profiles have included: take off, some navigational tasks, approach, final approach and landing. Evaluation of flight performance was done on basis of manoeuvres precision, registration of eye movements and progress in following attempts of flights.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

The obtained results indicated that in IFR conditions the symptoms of loss of spatial orientation were observed. In those cases the two types of reaction took place:
- type I of disorientation – no counteraction,
- type II of disorientation – counteraction.

Within the second type cases the oculographic registration indicated increasing intensity of eye saccadic movements and longer time of fixation.

In good meteorological flight conditions eye saccadic movements and significant changes of fixation time were not observed. It leads to the conclusion that no spatial disorientation was encountered.
Additional conclusion of this part of research was, that method of eye saccadic movements measurements could be used for detecting the loosing of spatial orientation during both simulated and real flights.

Certain flight manoeuvres provoke spatial disorientation more frequently than others [8]. When pilot is aware of such phenomenon then is possible his earlier reaction and correction. In such a case pilot performs the manoeuvre knowing possible perceptual and vestibular misinformation, which can be intellectually controlled through corrective information coming from the flight instruments and indicators. It was mentioned that spatial disorientation might occur in different phase of flight. Can special training counteract it? How does deal with it? The pilots usually ask these kinds of questions.

For the purpose of that paper we have defined spatial disorientation as a state characterised by the false perception of one's position in relation to the Earth surface, which is caused by the senses misinterpreting the pilot's position in space. We have limited this part of experiments to the spatial disorientation caused by the visual factors.
The reason of such decision was, that during our research and analysis we found that classic hexapod (Stewart type) motion system of our flight simulator is practically unusable for spatial disorientation research and training in terms of producing illusions caused by angular or linear accelerations.
For our practical purposes we will discuss only vision as the most important source of information, which provide orientation to pilots. In that manner vision can also be thought of as being the most important sense controlling flight situation. That visual dominance is a potential cause of illusions and disorientation during flight. Aircraft accidents have occurred because of illusions caused by limitations of our sense of vision. Pilot's awareness of these illusions is important step in the prevention of possible incidents and accidents. The reduction of aviation mishaps can be achieved through improvement of spatial disorientation understanding and development of pilot training programs.

In these works we considered hardware improvements and practical possibilities of simulator adaptation and construction of methodical foundations counteracting to occurrences of spatial disorientation. Flight simulator "Japetus" serves as a one element of the complex system used to demonstrate and estimate the spatial disorientation.
Realisation of this assignments demanded many changes in the simulator software. These changes refer to:
- introduction additional element of visualisation. Those elements are mainly connected with meteorological conditions,
- textures Of Baltic Sea with the coast line,
- lights of cities with respect of their localisation. They are situated in vicinity of airfields with regard their geographical co-ordinates and have to be taken into account accidental configurations of street lights lying in straight lines,
- textures of skies including lights of stars. Points of light are motionless,
  using accidental arrangement and diverse intensity of shining,
- upper limit of clouds (with angle in range 1-5^{o}) which is diagonal to natural horizon,
- using the special plane-target, which serves as a tracking point for training pilots to shift their attention. The control of plane-target should take place from positions of instructor,
  -profile of plane appearing in central section of visualisation of simulator, having possibility of moving oneself in range of height 50-3000 metres. and dynamics of plane TS-11.
- "freezing" of flight instrument position with possibility of return to normal indications after time defined by instructor,

EXPERIMENTAL METHODOLOGY OF SPATIAL ORIENTATION TRAINING.

The initial course was projected for military pilots and included both theoretical background of spatial disorientation and experimental flights . In the first phase of the course pilots were prepared through series of lectures concerning the occurrences of spatial disorientation and its consequences. The main goal of this preparation was to increase their knowledge about the phenomenon and achieve better understanding of SD problems.

There were two kinds of experimental flights. The first one consists of start, approach, final approach and landing according of NDB's (non direction beacons) system and runs in instrumental meteorological flying conditions (IFR) with strong turbulence. The second one consisted of repetition above-mentioned flight pattern without turbulence in visual flight conditions. The valuation of flying performances was achieved thanks registration of eye movement and progresses in following attempts of flights.

RESULTS AND CONCLUSION

Results indicated that in IFR conditions with strong turbulence symptoms of loss of spatial orientation were observed which in consequence led to worse performance of executed flights. In cases of loss of spatial orientation (almost 60% of all flights performed) two typical reactions were observed:
type I of disorientation - no counteraction – (20%) and type II of disorientation- counteraction reaction – (40%). The oculographic registration in first group indicated increasing intensity of eye saccadic and fixation probably caused by necessity of verification of flight parameters.

In second group there weren't significant changes in intensity of eye saccadic and fixation. This fact can be confirmation of type II spatial disorientation.

SD TRAINING POSSIBILITIES ON "GYRO- IPT" SIMULATOR

Polish Air Force Institute of Aviation Medicine has acquired "Gyro – IPT" training device which is designed mainly to conduct spatial disorientation training for pilots. Gyro – IPT has a wide possibilities of presentation of visually evoked illusions and illusions based on angular accelerations in three axes. Significant advantages of this device are extended editing options. They cover possibility of changing aerodynamic aircraft model, mission parameters, navigation aids etc. It allows development of country - specified training program in terms of used aircrafts, procedures and terrain. Apart from software options provided by the manufacturer we have developed some our own training procedures. Proposed training syllabus consists of three steps.
First part of training is prepared for cadets of last year of Polish Air Force Academy and pilots with low experience in flying in IFR conditions (III class military pilot).
Second part is designed for pilots with medium experience (II class military pilot).and those returning to flying duties after long absence (more than 6 months).
Third part covers most advanced aspects of spatial disorientation and is suitable for experienced pilots (I and master class military pilot).
Every part of syllabus is in some matters repetitive because is designed partially as a "refresher" for previous parts.
Total training time is 2 hours of practical exercises on simulator per step predecessed by 3 hours of lecture and presentation.

Currently available SD training sorties are:

1. Coriolis illusion emerging as a result of cross – stimulation of vestibular apparatus after rapid head movements during circular motion.
2. Somatogyral illusions – result of false perception of rotation through semicircular canals
3. Oculogravic illusions – false perception of motion of another object as a result of nystagmoidal movement of eyeballs after stimulation of vestibular system by angular acceleration
4. Advanced oculogravic illusions – false perception of motion of another object as a result of nystagmoidal movement of eyeballs after stimulation of vestibular system by angular and linear acceleration
5. Graveyard spiral – ceasing of perception of prolonged circular motion (despite its continuation)
6. Nystagmus – cyclic, involuntary eyeballs movements after stimulation of vestibular system with variable angular accelerations.

7. Leans illusion – false perception of wings not being level after subtreshold roll movement with supratreshold recovery from previous attitude.
8. Advanced version of the leans illusion – during complex roll and yaw subtreshold movements with supratreshold recovery from previous attitude.
9. Autokinesis illusion – false perception of movement of stationary light in darkness.
10. Illusions connected with wrong perception of attitude and distance caused by atypical dimensions of runway .
11. Dark hole illusions – caused by lack of auxiliary fixing light points in pilot's field of view.
12. False horizon illusions – false interpretation of visible horizon e.g. clouds lines.
13. Dark takeoff illusions – uncertainity in assessment of attitude without visual reference.
14. Sloped runway illusions – false perception of attitude in distance in mountain terrain.

GYRO – IPT is also equipped with "helicopter option" which means possibility of simulation one engine rotary wing aircrafts. Program for presentation and training SD for helicopter pilots is currently under development.

SD EXPERIMENTS ON HUMAN CARRYING CENTRIFUGE

Previously mentioned training devices have disadvantage of lacking possibility of simulation of gravitational environment similar to real flight conditions. "Japetus" flight simulator has no such possibility at all, "Gyro – IPT" capabilities are limited to angular accelerations of limited magnitude. Because of importance of acceleration induced illusions we decided to use human carrying centrifuge to set – up somatogyral and somatogravic illusions.
Main goal of this task was to project and verify acceleration profile, which should generate illusions in trained pilots. In our preliminary test the subjects were 6 pilot candidates with small or no previous flight experience. For this research we used Polish Air Force Institute of Aviation Medicine centrifuge. It is centrifuge with 9-meter rotating arm, which we think, has a better possibility to add linear acceleration to angular in order to set – up somatogravic illusions than short arm devices (Gyro – Lab). Our centrifuge has a free moving gondola, which's angle with arm is dependent on current acceleration in range from 24° for 1,1G to 15,5° for 4G. We didn't use acceleration greater than 4G because change of angle with greater acceleration is very small and we were mainly concerned about Gx not Gz acceleration.
During our experiments we measure an angle between real horizon and the line representing horizon in centrifuge cockpit. Test task for subject was maintaining with flight controls level of artificial horizon in accordance to perceived real horizon level. Value of the test was assessed on the base of conformance of phase of registered stick movement with gondola movement phase. We discovered high variability of results between subjects with maximal difference between best and worse result being 22°. Greatest disturbances of perception of gondola roll we discovered during centrifuge "creeping" with acceleration in order 1,4 – 1,5G. It is also moment of greater change in angle of bank from 0° for full stop to 48° for 1,5G. The results obtained revealed two important factors: firstly in one subject we observed high repeatability of angle of bank in consequent runs and secondly persistence of bank perception during centrifuge braking. First observation is of great importance suggesting that despite individual variations, susceptibility for SD on one subject is fairly stable what after further research in extended time period can give assumption to selection of candidates in aspect of SD susceptibility .

FINAL CONCLUSIONS.

During last few years our knowledge about both theoretical and practical aspects of spatial disorientation increased as a result of conducted research works. But question of providing some precautive measures against SD is very complex and still open. Because of its nature phenomenon of false perception of spatial attitude and motion is difficult to quantify and matter of development selection test is remote in time, but current works show some promising results especially in area of oculographic measurements. Further directions of research should be improvement of current training protocols and extension of training possibilities in terms of available simulators. But development of method estimating spatial disorientation if of great importance because apart from selection will allow us to validate current methods of training as a method of SD prevention and probably develop new ones with greater efficiency in preventing aircraft mishaps caused by this phenomenon.

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Sensibilisation pratique du personnel navigant à la désorientation spatiale dans les Armées françaises

(Spatial Disorientation Awareness Instruction Given to Aircrews Serving in the French Armed Forces)

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1 - INTRODUCTION

Le Personnel Navigant (PN) des Forces armées est soumis à des contraintes physiologiques liées soit à l'environnement soit aux performances de l'avion . Ces contraintes et leur incidence sur la sécurité des vols sont telles qu'il est apparu nécessaire de donner aux PN un minimum de connaissance à leur sujet. Leur enseignement fait l'objet d'une circulaire ministérielle relative à l'instruction aéromédicale du PN, qui en définit les grandes lignes.

Cette instruction est réalisée sous forme d'enseignement théorique délivré au cours de la formation professionnelle en école, l'autre partie pratique est réalisée au Laboratoire d'Etudes Médico-physiologiques 16/330 (LEMP) lors du début de l'instruction en vol. Le LEMP est une unité du Centre d'expériences aériennes militaires, localisée à Mont de marsan au sud-ouest de Bordeaux et est également le Département de Médecine opérationnelle de l'Institut de Médecine aérospatiale du Service de santé des armées, dont les autres départements se trouvent à Brétigny sur Orge en région parisienne.

Les stages d'instruction aéromédicale initiale au LEMP, d'une durée de 2 jours, comprennent des exposés didactiques et des démonstrations pratiques. Le programme d'instruction proposé porte principalement sur la désorientation spatiale et l'hypoxie. Une journée complète est consacrée à la désorientation spatiale.

2 – INSTRUCTION THEORIQUE

L'enseignement théorique porte sur les principes physiologiques du phénomène avec des exemples aéronautiques concrets et les conséquences sur la sécurité des vols que peuvent entraîner :

- Les illusions visuelles :
- erreurs de perception liées aux caractéristiques physiologiques du capteur visuel,
- erreurs d'interprétation liées à l'intégration centrale des simulations visuelles,
- facteurs d'environnement et dynamiques interférant avec la perception visuelle.

- Les illusions sensorielles d'origine vestibulaire :
- fonctionnement les otolithes et des canaux semi-circulaires,
- illusions dues aux stimulations de l'appareil vestibulaire et leurs mécanismes au cours de la pratique du pilotage.

- Les illusions sensorielles de cause mixte et leurs mécanismes.

Communication présentée lors du symposium RTO HFM sur la « Désorientation spatiale dans les véhicules militaires : causes, conséquences et remèdes », organisé à La Coruña, en Espagne, du 15 au 17 avril 2002, et éditée dans RTO-MP-086.

3 – INSTRUCTION PRATIQUE

Les démonstrations pratiques sont réalisées grâce à 3 ateliers :

3.1. Atelier d'illusions visuelles

L'atelier d'illusions visuelles comprend une batterie de tests visuels et un diaporama qui présentent :

* illusion de taille,
* illusion de perspective,
* illusion concernant la vision des couleurs,
* illusion concernant la vision du relief,
* illusion concernant le mouvement.

3.2. Cabine inclinable

Elle permet la démonstration d'illusions d'inclinaison par rapport aux axes de roulis et de tangage par modification de l'action de la force de gravité sur les otolithes ou par interaction de références visuelles variables de l'environnement.

3.3. Générateur d'illusions sensorielles

Le générateur d'illusions sensorielles (GIS) qui permet la démonstration du phénomène de désorientation spatiale par stimulation des canaux semi-circulaires et des otolithes de l'appareil vestibulaire selon un mode infraliminaire ou supra liminaire.

4 – DESCRIPTION DU GIS

Le LEMP est équipé du générateur d'illusions sensorielles depuis 1985 ; cet appareil, de conception originale a été réalisé par les Ateliers de Révision de l'Armée de l'air de Bordeaux Beauséjour et permet de reproduire, au niveau du sol, les erreurs de perception des mouvements et de positionnement telles qu'elles peuvent être rencontrées en situation aéronautique.

Le GIS peut être décomposé en deux parties : la régie fixe et la partie tournante.

La **régie** comprend :

- le pupitre de commande permettant le contrôle de la partie tournante,
- l'armoire de puissance permettant la mise en fonctionnement des motorisations de la partie tournante,
- et l'ensemble des moyens audiovisuels permettant l'enregistrement des séances d'instruction.

La **partie tournante** permet de mobiliser la nacelle dans laquelle se trouve le pilote en instruction.

- le bras principal d'une longueur de trois mètres est mis en rotation par le moteur principal et supporte à son extrémité le bras lacet,
- ce bras lacet supporte l'ensemble bras tangage et nacelle et permet une mobilisation dans l'axe de lacet de la cabine grâce à la motorisation lacet,
- le bras tangage forme un demi-cadre autour de la nacelle et lui autorise des mouvements en tangage grâce à la motorisation tangage et des mouvements en roulis grâce à la motorisation roulis.
- la nacelle est ainsi mobile selon 4 degrés de liberté.

Cette **nacelle** est constituée d'une cabine en matériau opaque équipée d'un siège Martin Baker type MK IV, d'une planche de bord comportant un horizon occultable, d'un manche de profondeur et de palonniers.

Ainsi, le sujet embarqué se retrouve dans une configuration de vol sans visibilité avec pour seules références ses informations sensorielles vestibulaires et proprioceptives et les données visuelles occultables de la planche de bord (horizon-boule) et du hublot de porte. Il pourra grâce au manche de profondeur avoir des actions sur les mouvements en roulis et tangage lorsque l'opérateur du pupitre l'y autorise.

La mise en rotation de l'ensemble mobile va permettre de générer des accélérations linéaires et angulaires ; ces accélérations pourront être infraliminaires et créant donc des forces d'inertie non détectées par les capteurs sensoriels ou supraliminaires et créant ainsi des forces d'inertie enregistrées par ces capteurs.

Le GIS est utilisé dans le cadre des stages d'instruction aéromédicale initiale organisés par le LEMP et dispensés au profit du Personnel Navigant de l'Armée de l'air. Une convention avec l'Aviation légère de l'Armée de terre (ALAT) prévoit des stages "illusions sensorielles" pour les pilotes en formation "vol aux instruments" à l'Ecole d'application de Dax.

En 1996, le GIS a bénéficié d'une rénovation dont le but était de diminuer les informations proprioceptives ressenties par le pilote embarqué, afin de stimuler principalement les capteurs vestibulaires. De plus cette rénovation a permis également d'intégrer des illusions visuelles et oculo-vestibulaires.

La rénovation mécanique a permis le remplacement des motorisations secondaires (roulis, tangage et lacet) par des ensembles à jeu réduit restituant une plus grande souplesse des déplacements. La nacelle en matériau composite a été complètement reconstruite avec une forme assurant une meilleure adéquation avec le cadre support, ce qui a permis une augmentation de l'amplitude des degrés de liberté permettant d'atteindre 50° en roulis et en tangage.

La rénovation informatique a vu l'installation d'un nouvel ensemble ordinateur et logiciel permettant:

- la programmation de profils,
- l'exécution de profils préenregistrés,
- l'enchaînement de différents profils,
- l'acquisition de profils lors du fonctionnement en mode manuel ou automatique,
- la restitution et l'analyse de ces profils,
- la commande en mode manuel grâce à l'ordinateur,
- la conservation du mode manuel depuis le pupitre.

Ainsi, le système peut fonctionner selon trois modes :

- un mode manuel grâce au pupitre,
- un mode manuel grâce au système informatique,
- un mode programmé grâce au système informatique.

5 – PROTOCOLE DE DEMONSTRATION

Les nouvelles possibilités de manœuvre du GIS ont permis de mettre en place un protocole de démonstration prévoyant deux phases successives : bras principal à l'arrêt puis bras principal en mouvement.

Le **bras principal étant à l'arrêt**, on met en évidence les illusions suivantes :

Tout d'abord l'illusion autocinétique : en fixant un point lumineux, la nacelle étant immobile toutes lumières éteintes.

Ensuite, on met en évidence les seuils de sensibilité lors des accélérations linéaires en tangage puis en roulis et le seuil de sensibilité lors des accélérations angulaires par une accélération infraliminaire en lacet.

Puis on crée une illusion somatogyrale par une mise en accélération supraliminaire en lacet, et on termine cette phase par l'illusion oculogyrale au cours d'une mise en lacet.

La seconde phase réalisée avec le **bras principal en mouvement** met en évidence les illusions suivantes :

- illusion somatogravique de piqué : la nacelle est horizontale, l'arrière regardant l'axe de rotation du bras principal, la mise en rotation de ce bras entraîne une sensation de piqué.
- illusion somatogravique de cabré : la nacelle reste horizontale, l'avant regardant l'axe de rotation du bras principal, la mise en rotation de celui-ci entraîne une sensation de cabré.
- illusion somatogravique d'inversion : dans la configuration de l'illusion somatogravique de cabré, on génère un cabré réel à 40° avec retour rapide à l'horizontale : le pilote perçoit une sensation de passage sur le dos ou de bascule en arrière.
- effet de Coriolis enfin, dans la configuration de l'illusion somatogravique de cabré, le pilote exécute un mouvement de bascule de la tête dans un plan perpendiculaire au plan de rotation du GIS déclenchant une sensation de roulis.

Les principales illusions d'origine vestibulaires rencontrées en aéronautique peuvent ainsi être passées en revue. Au terme de cette démonstration le stagiaire est amené à mettre totalement en doute ses propres sensations et à faire une confiance absolue à ses instruments de bord ; le phénomène de la dominance visuelle instrumentale est alors d'une extrême réalité.

6 – CONCLUSION

Une enquête d'opinion est réalisée à l'issue de l'instruction auprès des stagiaires. Dans celle-ci, afin d'évaluer l'intérêt du stage réalisé au LEMP, quatre questions sont posées.

- Le sujet des illusions sensorielles vous avait-il été présenté auparavant ?
Une réponse positive a été faite pour 68% des stagiaires Air et 83% des stagiaires Terre.

- Le stage au LEMP vous a-t-il apporté une information complémentaire ?
Une réponse positive a été faite dans 100% des cas.

- Après le stage, l'instruction sur les illusions sensorielles vous semble-t-elle suffisante ?
Une réponse positive a été faite dans 96% des cas.

- Les conduites à tenir face aux situations dangereuses en vol vous ont-elles paru bien développées ?
Une réponse positive a été faite pour 92% des stagiaires Air et pour 95% des stagiaires Terre.

Telles sont les modalités de présentation pratique du phénomène de désorientation spatiale en vol pour le personnel navigant des Forces armées françaises dont l'objectif est d'améliorer la Sécurité des vols.

Assessment of Motion Devices Used for Spatial Orientation Research and Training

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Summary

There are many unresolved issues related to motion-based simulators including: 1) should they even be used, 2) if so, what drive configurations might be preferred and to what aspects of flight should they be applied, 3) what motion cues and artifacts are critical, 4) what drive algorithm or set of drive algorithms best utilizes the motion capabilities of a given configuration to emulate critical aircraft motion cues while producing minimal artifacts, and 5) how can pilot-driven algorithms be made more effective at teaching recovery from the perceptual conflicts of spatial disorientation? None of these questions are answered by this paper. What the paper does contain is a description of the capability of a computer simulation of motion simulators that can be used to help quantitatively address these questions. A sample aircraft maneuver is evaluated for several variants of drive configuration and drive algorithm to illustrate the measures for quantitative comparison of motion systems and the level of effort and input data required to make the comparison. The paper indicates the status of an ongoing effort to develop a modeling tool for use by the spatial orientation and flight simulation communities to gain further understanding of the role of motion simulators.

1 INTRODUCTION

A fundamental characteristic of flight simulators is that changes in the visual out-the-window scene and instrument readings are pilot-driven in response to pilot sensory information obtained from those same visuals. Only commercial aviation makes significant use of motion simulators where the motion is part of the pilot-driven, pilot-sensed loop. The nature and relevance of motion cuing to general pilot proficiency is not well understood [1], although there are situations such as recovery from the sensory conflicts of illusion-producing motions where the motion requirements of the simulator are clearly understood and the presence of motion in the pilot-driven, pilot sensed loop is critical [3]. Assessment of the value of motion cues to general pilot proficiency has been investigated with mixed results. A US DOT study found the incremental value of motion to be immeasurable [4]. Others have concluded that prior experience with motion-based simulators was destined to fail, since the technologies applied to accomplish motion and synchronize it with visual cues has been very poor compared to present day capability [6]. In the case of the U.S. Air Force, fixed base is the simulator form used for both heavy and tactical classes of aircraft.

An important attribute of a motion-based flight simulator is rapid response to pilot input. The only perceived delay should be that of the particular aircraft flight control system being simulated. Any delay in response of the motion system must be recognized as 'un-airplane-like' and reduced to the smallest value possible. Further, synchronization between the visual and motion system responses must be minimized to

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avoid the possibilities of simulator sickness and negative training. These response traits can be evaluated via simulation or test by comparing the visual and motion response of the simulator with the aircraft motion that drives the simulation. Motion system delay via simulation was considered in reference [9] for a high g-trainer controlled to operate as a flight simulator. Evaluation of motion system delay via simulation requires an integrated model of the simulator dynamic system, including its motors and feedback control system and a predictor of human perception of motion.

A more fundamental issue with motion-based simulators is the degree to which an ideal motion-producing device, one with no time delay, can produce perceived motion in the rider that is similar to that perceived in an aircraft while not producing any deleterious motion artifacts. It can be categorically stated that no practical ground-based motion system can reproduce all motions that an aircraft is capable of producing since the simulator remains attached to the ground. Likewise, a ground-based motion system cannot emulate any aircraft motion except steady flight without creating some motion artifact. The drive mechanism used almost exclusively in motion simulators, is the Stewart platform. The philosophy of this drive algorithm is to provide acceleration onset cues that are 'airplane-like' followed by sub-threshold return of the actuators to their neutral position. The virtue of the Stewart platform is the ability to provide the onset of *any* aircraft transient motion. Its deficit is the inability to produce high and sustained g levels of aircraft, particularly tactical and aerobatic aircraft. Further, each return to sub-threshold acceleration level is a motion artifact. Drive mechanisms that have actuators configured in a series or cascade arrangement have been used to produce the sustained g-levels and sustained angular rates experienced in flight. They have found application for simulating specific maneuvers such as spatial illusions [5] and super-maneuvers that make use of thrust vectoring [7][11]. However, any particular configuration of a cascade device appears to be best suited to specific maneuvers, making it difficult to provide general simulator capability with a single device. Further, artifacts are always created by the arm rotation used to produce continuous acceleration or angular rate. While a fixed base simulator has no artifacts, it also has no motion cues. Thus, no motion (or no-motion) alternative is clearly superior. It seems appropriate to reexamine the statement "no motion is better than bad motion" in light of these observations and the recognition of improvements in motion control that are now available. The unresolved issue in attempting to incorporate the advantages of motion into flight simulators is not whether a Stewart platform or a centrifugal arm is best suited, but whether a high fidelity motion simulator can be developed that can accomplish the essential transient and continuous motion cues of flight with acceptably inconsequential artifacts.

This paper reports the progress of an ongoing study to investigate the capability to provide both *transient and continuous* motion cues to a pilot-driven simulator. To find an effective means to do so for any maneuver of any aircraft would markedly expand simulator usefulness for training to maintain spatial orientation and recover from spatial disorientation and for pilot training in general. But this is perhaps more than can be expected. To find a better means to do so only for selected maneuvers such as those that create vestibular illusions would provide a lesser but still significant expansion of simulator usefulness and, perhaps more importantly, help to clarify the role of motion in pilot training. Conclusions in this study are based on the output of a model of the vestibular end organ that attempts to predict perceived motion. Verification of conclusions must be obtained by subject testing in a prototype device.

2 Drive Mechanism Configurations

How many degrees of freedom (DoF) should a motion-based simulator possess? Since an aircraft possesses six degrees of freedom, three translational and three angular, intuitively it would seem that the drive should also contain six DoF. Such is the case for the Stewart platform. It consists of six prismatic (linear) actuators configured to act in parallel on the platform that, for flight simulator, is a replica of an aircraft cockpit. Because it possesses six DoF, it can duplicate the onset of all short duration motions of flight. It is, however, limited by stroke of the prismatic joints to providing onset cues for longer duration motions and accelerations. The Stewart platform is particularly suited to replicating the transients of helicopter motion and has found significant application in large transport aircraft and commercial airliners.

The other significant class of platforms used to produce motion in flight simulators is the cascade configuration which consists of revolute and prismatic joints configured in serial link or chain fashion with the cockpit attached at the end of the last link. Such cascaded devices can provide transient and continuous angular rates, transient and continuous linear accelerations at elevated levels, and transient angular accelerations all of which are present in the flight of high speed aircraft. Cascade mechanisms have been used predominantly to demonstrate spatial disorientation. They typically have three or four actuated joints which preclude simultaneous control of more than that number of degrees of platform freedom. The rationale for limiting control capability apparently is that some cues cannot be justified economically.

Table 1 summarizes the basic kinematic structure of illustrative motion-based devices built for use in flight simulators, where ***R*** and ***P*** designate revolute and prismatic joints, respectively. Kinematic configuration is not fully specified by kinematic structure. In addition to joint arrangement and type, the relative orientations of their axes of motion and the distance between joints are critical design variables that can affect the ability to duplicate a specific aircraft motion. In this study, a particular 3 DoF R-R-R cascade configuration, hereafter referred to as the 3R cascade drive, was selected for investigation that can be tailored to represent the DES, the IPT and certain 3 DoF motions performed by the ASDT. The relative orientation and distance between the three axes is depicted in Figure 1 for the device at rest. The parameters that can be varied are length L_2 of the planetary arm and distance L_3 of the vestibular point above or below the yoke point (YP) where second and third axes intersect. Three coordinate frames are indicated in Figure 1:

Frame 0 - Base Frame The zero frame is fixed to the earth with its origin, O_0, on the planetary axis and at the same elevation as the YP. z_0 is the axis of (vertical) planetary rotation and the angle swept out by the planetary arm is q_1. Note that the angular velocity is positive for clockwise rotation as seen from above (the DES rotates clockwise). When q_1 is a multiple of $2\pi, x_0$ is pointed along the arm towards YP. y_0 forms a right hand orthogonal coordinate set.

Frame v - Vehicle Frame Frame v is attached to the cab with its origin, O_v at the vestibular point. Axes are defined as conventional aircraft axes: x_v points in the forward facing direction of the pilot and is his roll axis, y_v points rightward along the pilot's pitch axis and z_v points downward along the pilot's yaw axis.

Device	# DoF	Joint Arrangement, Type	Owner or Mfr.
Dynamic Environment Simulator (DES)	3	Serial, R-R-R	WPAFB
GFET	3	Serial, R-R-R	ETC
IPT	4	Hybrid Serial/Parallel, R-P-R-R	ETC
Advanced Spatial Disorientation Trainer	4	Serial, R-R-R-R	Brooks AFB
Level C Flight Simulator	6	Parallel, P-P-P-P-P-P	FAA
Desdemona	6	Serial, P-P-P-R-R-R	AMST Corp

Table 1: Tabulation of the basic kinematic structure of illustrative motion-based simulators.

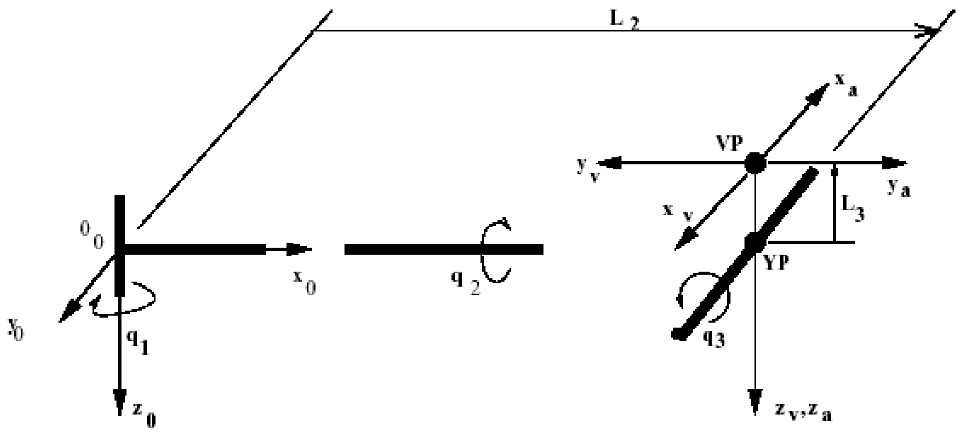

Figure 1: Coordinate frame definitions for the 3 DoF cascade drive configuration implemented in the kinematic model (shown at rest).

Frame a - Anatomical Frame Frame *a* is attached to the cab with its origin, O_a coincident with O_v. Axes are defined in anatomical directions: x_a points in the rearward facing direction of the pilot y_a points leftward with respect to the pilot and z_a points downward. Frame *a* is fixed with respect to frame *v* since no head motion is assumed.

In Figure 1, the rider is shown facing tangent to the path of the VP and in the forward direction for clockwise rotation of the planetary arm. Other rider orientations can also be specified in the input file for the simulation. Frame-*v* is used to express the state vectors in conventional aircraft components. Frame-*a* is used to express vectors in conventional anatomical components. The three joint variables $[q_1, q_2, q_3]$ define device position. It is noted in Figure 1 that for the centrifuge at rest, $q_1 = q_2 = \pi / 2$ whereas $q_3 = 0$.

3 Model Description

How the number, type, orientation and spacing of the actuated joints influence the ability of a particular configuration to provide the requisite motion sensations and only non-deleterious artifacts can be quantified by modeling the *drive algorithm* that converts desired aircraft accelerations into commands to the joints of the drive mechanism and the *forward kinematics equation* of the drive mechanism that convert the joint commands into equivalent platform accelerations. If the drive algorithm were the mathematical inverse of the forward kinematics equations, the platform accelerations would precisely match the desired aircraft accelerations, the simulator would be precise at reproducing aircraft motion and there would be no motion artifacts. Because it is not the inverse for any practical drive mechanisms, this kinematic model is a useful tool for quantitatively comparing the performance of various drive algorithms and drive mechanism configurations. By consciously excluding from the model, the dynamic effects of the drive and motor and the delay of the feedback control strategy implemented, configuration alternatives can be more objectively evaluated and with a much reduced set of device characteristics.

Figure 2 identifies the eight Matlab modules that comprise the kinematic model used for this study. Input to the model, module 'Sensed Acceleration Input', is the sensed acceleration profile (including gravity) in the aircraft at the pilot vestibular point. The module 'Controller Commands' contains the drive algorithm. The forward kinematic equations are contained in the 'Output Processor' module. The forward kinematics portion of the model can be viewed as the plant or physical device and the drive algorithm as a command that drives the plant. There is one forward kinematic equation associated with a particular kinematic configuration. There may be multiple drive algorithms associated with it. No other aspects of the motion simulator are included in the kinematic model. The modular structure minimizes the change out required to evaluate different simulators. Primary output data from the model is the level of DFS fidelity attainable and the magnitude of artifacts. Young's model of the vestibular end organ [12][13][14] is implemented in the module 'Vestibular Model' to evaluate the effects of accommodation and sub-threshold signals on perceived motion. The module 'Vestibular Model' also contains a scalar metric for measuring the fidelity of a maneuver that is the integral over the maneuver time of the root-sum-square of the normalized errors in each of the six acceleration components. The other modules, that are less relevant to the topic of this paper, are described briefly in figure 2.

The model was implemented with MATLAB™ and SIMULINK™ software.* The kinematic model becomes a dynamic model when the module "Ideal Plant Dynamics' is replaced by a model of the plant, drive motors and feedback controller for a particular motion simulator. The dynamic model of the GFET Tactical Flight Simulator is described in reference [9].

3.1 Sample Maneuver

A simple maneuver is used here to illustrate use of the model in evaluating the fidelity of a motion simulator. It is transition from steady level flight into a coordinated steady turn with a constant climb or descent, which can develop analytically. As will be illustrated, it is not a trivial maneuver to accomplish with fidelity by the motion drives investigated herein.

The aircraft is assumed to transition from steady, wings level flight to a steady, climbing (or descending) turn with bank angle $\phi(t)$ prescribed as a function of time. The transition is flown in such a way that the turn is coordinated at any instant. Following the kinematic definitions of Etkin [2], the orientation of an aircraft relative to an earth fixed frame is given by three Euler angles, $[\psi, \theta, \phi]$, a set of sequential rotations about axes *z*, then *y* and then *x* of the aircraft body frame (frame-*v* in this document). The associated Euler angular rates, $[\dot{\psi}, \dot{\theta}, \dot{\phi}]$, are related to the body rates, $[p,q,r]$ by the equations:

$$
\begin{aligned}
\dot{\psi} &= (q \sin\phi + r\cos\phi)\sec\theta \\
\dot{\theta} &= q\cos\phi - r\sin\phi \\
\dot{\phi} &= p + (q\sin\phi + r\cos\phi)\tan\theta
\end{aligned}
\tag{1}
$$

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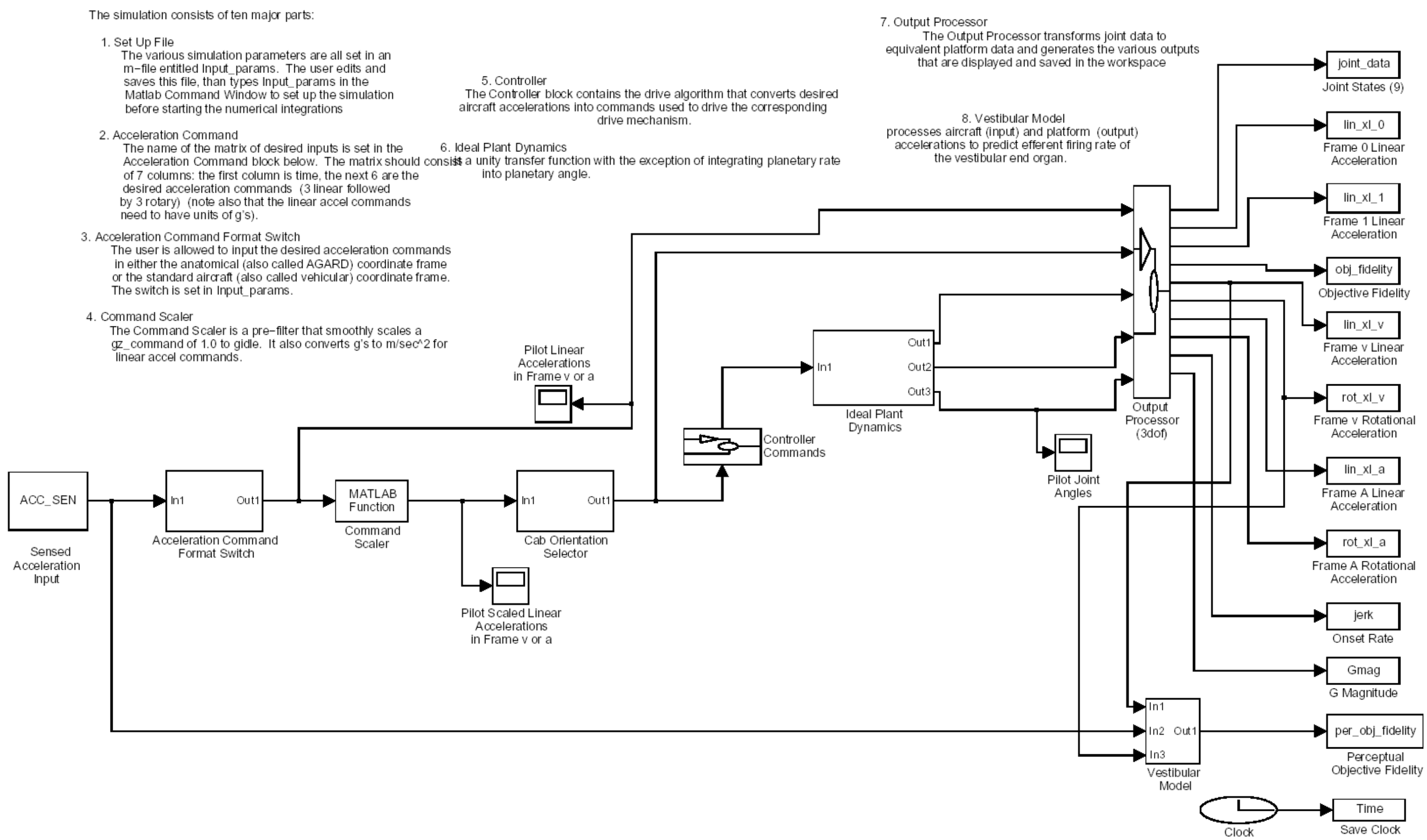

Figure 2: Simulink module representation of the kinematic model for motion simulator drives.

The g-level n, equation 2, turn rate $\dot{\psi}$, equation 3 and turn radius R, equation 4 that describe aircraft motion in a coordinated turn are also adapted from Etkin [2]:

$$n = \sec\phi \tag{2}$$

$$\dot{\psi} = \frac{g}{V}\tan\phi \tag{3}$$

$$R = V^2 / (g \tan\phi) \tag{4}$$

where g is the acceleration of gravity and V is aircraft speed. Then, the frame-v components of the acceleration commands at the aircraft center of mass are given by:

$$\begin{Bmatrix} G_x \\ G_y \\ G_z \\ \alpha_x \\ \alpha_y \\ \alpha_z \end{Bmatrix}_v = \begin{Bmatrix} 0 \\ 0 \\ -n(t) \\ \dot{p}(t) \\ \dot{q}(t) \\ \dot{r}(t) \end{Bmatrix}_v \tag{5}$$

where G_i is the i^{th} component of sensed rectilinear acceleration normalized by g, α_i is the i^{th} component of angular acceleration, and 'sensed' is used here to mean inclusion of gravity. Alternatively, when the pilot vestibular location is displaced from the aircraft center of mass by a distance $[r_x, r_z]$, the resulting profile is given by:

$$\begin{Bmatrix} G_x \\ G_y \\ G_z \\ \alpha_x \\ \alpha_y \\ \alpha_z \end{Bmatrix} = \begin{Bmatrix} \left(r_x\left(r^2 - q^2\right) - r_z rp + \dot{q}r_z\right)/g \\ \left(r_x pq + r_z qr + \dot{r}r_x - \dot{p}r_z\right)/g \\ -n(t) + \left(r_x rp - r_z\left(q^2 + p^2\right) - \dot{q}r_x\right)/g \\ \dot{p}(t) \\ \dot{q}(t) \\ \dot{r}(t) \end{Bmatrix} 1/g \tag{6}$$

where n is given as a function of ϕ by equation 2 and the body rates [p, q, r] and their derivatives can be determined as a function of ϕ using equations 1. The assumed bank angle ϕ for three phases of the maneuver are:

Steady, level flight, $t < T_s$:

$$\phi(t) = 0 \tag{7}$$

Transition, $T_s < t < T_f$:

$$\phi(t) = \frac{\phi_f}{2}\left(1 - \cos\omega t\right) \tag{8}$$

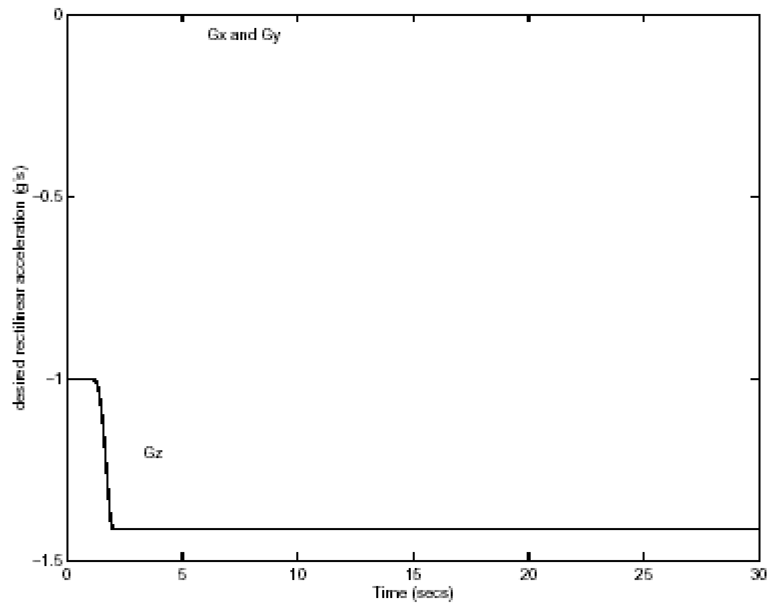

Figure 3: G_x, G_y, G_z sensed accelerations for the sample maneuver with $r_x = r_z = 0$.

Steady coordinated turn, $t > T_f$:

$$\phi(t) = \phi_f \tag{9}$$

where T_s and T_f are the start and finish times of the transition from steady level flight to a steady coordinated turn.

Equations 5 are evaluated for transition to a $\sqrt{2}g$ turn in 1 second starting after 1 second of level flight and produce linear and angular acceleration commands as indicated in figures 3 and 4, respectively. The large spikes in α_x result from the step change in prescribed roll acceleration $\ddot{\phi}$ at the start and end of the transition. In figure 5, where the vestibular point is located 3m forward $(r_x = 3m)$ and 0.5m above the center of mass $(r_z = -0.5m)$, there is a large spike in G_y, as well, produced by the roll acceleration for the same transition.

3.2 Forward Kinematic Equations

The equation that relates frame v components of sensed acceleration to the plant joint states for the 3DoF revolute drive of figure 1 is:

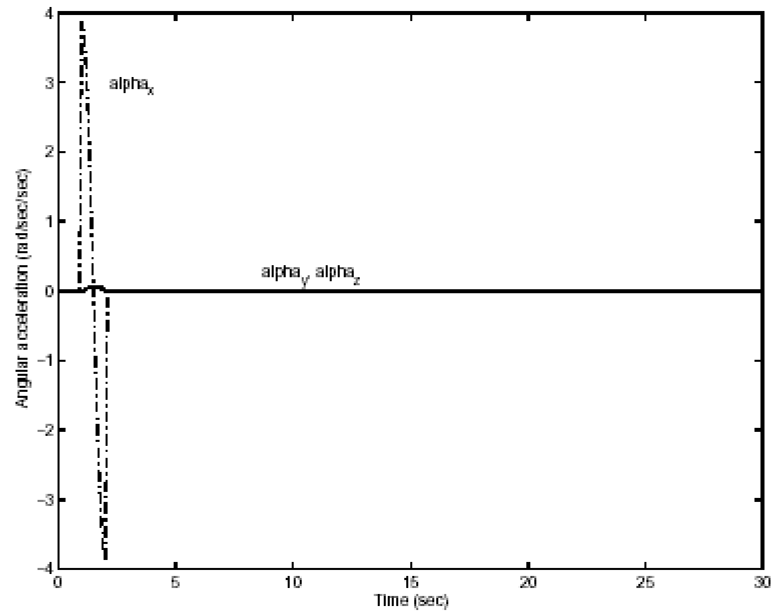

Figure 4: Angular accelerations for the sample maneuver.

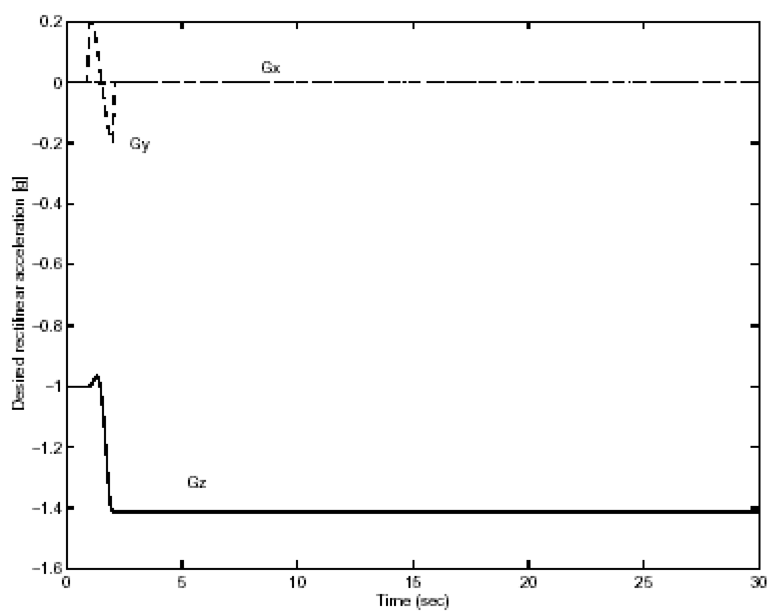

Figure 5: G_x, G_y, G_z sensed accelerations for the sample maneuver with $r_x = 3m$ and $r_z = -0.5m$.

$$\begin{Bmatrix} \ddot{x}_s \\ \ddot{y}_s \\ \ddot{z}_s \\ \cdots \\ \alpha_x \\ \alpha_y \\ \alpha_z \end{Bmatrix}_v = J_v \begin{Bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{Bmatrix} + \left[\dot{J}_v\right] \begin{Bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{Bmatrix} - g \begin{Bmatrix} C_2 \\ S_2 S_3 \\ C_3 S_2 \\ \cdots\cdots \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{10}$$

where $[\ddot{x}_s, \ddot{y}_s, \ddot{z}_s]$ are the rectilinear components of sensed acceleration (not normalized), S_i and C_i are the sine and cosine of joint variable q_i, the single and double dots over joint variables indicate their first and second derivatives, respectively, J_v is given by

$$J_v = \begin{bmatrix} -S_2(L_2 + L_3 S_3) & -L_3 C_3 & 0 \\ C_2(L_3 + L_2 S_3) & 0 & L_3 \\ L_2 C_2 C_3 & 0 & 0 \\ \cdots\cdots\cdots\cdots & \cdots\cdots & \cdots \\ C_2 & 0 & 1 \\ S_2 S_3 & C_3 & 0 \\ C_3 S_2 & -S_3 & 0 \end{bmatrix} \tag{11}$$

and $\dot{J}_v$ is given by

$$\begin{bmatrix} -L_3 C_3 S_2 (C_2 \dot{q}_1 + \dot{q}_3) & L_3 S_3 \dot{q}_3 & L_3 (S_3 \dot{q}_2 - C_3 S_2 \dot{q}_1) \\ -C_3 \left(L_2 + L_3 S_2^2 S_3\right)\dot{q}_1 - L_3 C_3^2 S_2 \dot{q}_2 & L_3 C_3 (S_3 \dot{q}_2 - C_3 S_2 \dot{q}_1) & 0 \\ \left(L_3\left(3 + C_{2q2} - 2C_{2q3} S_2^2\right) + 4L_2 S_3\right)\dot{q}_1 / 4 & L_3 C_3 (S_2 S_3 \dot{q}_1 + C_3 \dot{q}_2) & L_3 C_2 \dot{q}_1 + \dot{q}_3 \\ +2L_3\left(S_2 S_{2q3} q_2 + 2C_2 q_3\right)/4 & & \\ \cdots\cdots\cdots\cdots\cdots\cdots & \cdots\cdots\cdots\cdots & \cdots\cdots\cdots\cdots \\ 0 & -S_2 \dot{q}_1 & 0 \\ 0 & C_2 S_3 \dot{q}_1 & C_3 S_2 \dot{q}_1 - S_3 \dot{q}_2 \\ 0 & C_2 C_3 \dot{q}_1 & -S_2 S_3 \dot{q}_1 - C_3 \dot{q}_2 \end{bmatrix} \tag{12}$$

It can be observed in equation 10 that precise duplication of all six components of aircraft acceleration is possible only when simulating an aircraft in steady state. To illustrate, if $\dot{q}_1 =$ *const.*, $q_2 =$ *const.* and $q_3 =$ *const.*, the three components of aircraft rectilinear acceleration, $\ddot{x}_s, \ddot{y}_s$ and $\ddot{z}_s$ can be maintained at constant, non-zero values and the aircraft angular accelerations α_x, α_y and α_z are zero as required for steady flight. However, if the drive must be accelerated to change the aircraft rectilinear accelerations as a function of time in a specified way, then drive angular accelerations $\ddot{q}_1, \ddot{q}_2$ and $\ddot{q}_3$ must be specified as a function of time. As a result, the aircraft angular acceleration values are also specified as a function of time and, hence, will not match the desired aircraft angular acceleration profiles. Aircraft maneuvers that include variable levels of acceleration, such as transition between steady flight conditions, are the source of artifacts in motion simulators with revolute joints.

The forward kinematic equation 10 is embedded in the 'Output Processor' module of figure 2. It is valid for all of the motion type devices considered in this paper. Note for example a 1*g*-cascaded drive is modeled by setting $L_2 = 0$, a > 1*g*-cascaded drive by setting L_2 equal to planetary arm length. In general, the forward kinematic equation differs for each drive configuration. The forward kinematic equation can be generated symbolically for any cascade device using model development procedures for robotic devices [10] and the Mathematica™ software.*

3.3 Selected Drive Algorithms

A range drive algorithms can be devised for a particular drive configuration with the goal of providing fidelity of selected critical motion cues of a particular aircraft maneuver while also creating minimal artifacts. Three drive algorithms are presented here that provide different sets of critical cues, applicable for the 3R cascade configuration. Input to each is instantaneous aircraft data that makes the algorithm suitable for a pilot-driven simulator. In cases I and III where the moment arm L_2 is finite in length, the platform is assumed to be facing tangent to its trajectory about joint 1.

3.3.1 Case I: Drive Algorithm for Otolithic Critical Perception

While there are six independent components of vestibular acceleration experienced by an aircraft pilot, there are only three joint variables available to produce a desired response for the 3DoF-cascaded simulator. Thus, all vestibular components cannot be simultaneously controlled to their desired values. In this section, control of the linear acceleration components is formulated as the command for driving the motion system. This permits the motion system to control the magnitude and orientation of the sensed g-vector relative to the simulator to be that experienced in an aircraft with the desired acceleration profile. Thus, the otoliths of the rider of the simulator are exposed to the appropriate motion cues.

Joint commands q_i are related to the aircraft (frame-*v*) linear accelerations by solving the upper partition of equation 10 for joint angular accelerations in terms of the frame-*v* linear accelerations. L_3 is set to a nominal value of zero in solving since it is desirable to limit the nonlinear coupling between components of commanded joint acceleration. Note the upper partition of the matrix J_v defined by equation 10 is mathematically singular for this assumption. Thus, the matrix cannot be inverted and the physical interpretation is that there is no way to directly control all three components of a/c linear acceleration with this kinematic configuration. An inverse solution can be *devised* that has the desired effect.

Planetary Commands - The sensed acceleration level a_{mag} can be determined by taking the magnitude of upper partition of equation 10:

$$\begin{aligned} a_{mag} &= \sqrt{\ddot{x}_S^2 + \ddot{y}_S^2 + \ddot{z}_S^2} \\ &= \sqrt{\left(-L_2\dot{q}_1^2\right)^2 + \left(-g\right)^2 + \left(L_2\ddot{q}_1\right)^2} \end{aligned} \qquad (13)$$

Equation 13 is frequently referred to as the centrifuge characteristic equation [8]. It is a highly nonlinear differential equation that relates the joint space variable $\dot{q}_1$ to task space (i.e. frame *v*) variable a_{mag}. It (presumably) cannot be solved analytically. Further, numerical solution must be accomplished in two parts depending on whether the centrifuge is accelerating or decelerating. A useful drive algorithm for the first

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* Mathmatica is a registered trademark of Wolfram Research, Inc., Champaign, IL

joint (the planetary arm speed) can be established by setting $\ddot{q}_1 = 0$ in the characteristic equation in order to determine a commanded angular rate $\dot{q}_1^{com}$:

$$\dot{q}_1^{com} \approx \sqrt[4]{\left(a_{mag} / L_2\right)^2 - \left(g / L_2\right)^2} \tag{14}$$

Platform Orientation Commands - The second row of equation 10 can be solved for the ‘command’ joint angle q_2^{com} and is given by

$$q_i^{com} = \arcsin\left\{-b/2a \pm \sqrt{(b/2a)^2 - c/a}\right\} \tag{15}$$

where $i = 2$, $a = L_2^2\left(\ddot{q}_1^{com}\right)^2 + g^2, b = 2\ddot{x}_s^{des} L_2 \ddot{q}_1^{com}$ and $c = \left(\ddot{x}_s^{des}\right)^2 - g^2$. Since q_2 is always positive, the positive root from the quadratic is used.

The third row of equation 10 can be solved for the ‘command’ joint angle q_3^{com} and is given by equation 15 where $i = 3$, $a = L_2^2\left(\dot{q}_1^{com}\right)^4 + g^2 \sin^2 q_2^{com}, b = \left(\ddot{y}_s^{des} - L_2 \ddot{q}_1^{com} \cos q_2^{com}\right) 2g \sin q_2^{com}$ and $c = \left(\ddot{y}_s^{des} - L_2 \ddot{q}_1^{com} \cos q_2^{com}\right)^2 - L_2^2\left(\dot{q}_1^{com}\right)^4$. For the computation of q_3, the sign of the radical in equation 15 is determined by the sign of $\ddot{q}_1^{com}$. Planetary angular acceleration $\ddot{q}_1$ appears in the equation and must be measured, estimated or omitted. Because platform pitch is strongly effected by planetary angular acceleration and it should not be omitted. It can be obtained by differentiating equation 14.

The drive algorithm presented above is that which drives the dynamic model of motion drives (not presented here). The dynamic model presumes that the platform motion is pilot-driven and hence is configured to only accept instantaneous inputs that are available from a simulator's aircraft model. For the kinematic model of motion drives, additional knowledge of the aircraft maneuver is needed to produce the first and second derivatives of the joint variables, $[\dot{q}_1, \dot{q}_2]$ and $[\ddot{q}_1, \ddot{q}_2]$ that, for the dynamic model, are produced by the model in response the drive algorithm. These derivatives can be determined for analytical maneuvers such as the one presented in this paper by sequentially evaluating two differentiations of equation 15, their functional form being:

$$\dot{q}_2 = \dot{q}_2\left(\dot{q}_1, \ddot{q}_1, q_2\right) \tag{16}$$

$$\ddot{q}_2 = \ddot{q}_2\left(\dot{q}_1, \ddot{q}_1, q_1^{(3)}, q_2, \dot{q}_2\right) \tag{17}$$

$$\dot{q}_3 = \dot{q}_3\left(\dot{q}_1, \ddot{q}_1, q_1^{(3)}, q_2, \dot{q}_3\right) \tag{18}$$

$$\ddot{q}_3 = \ddot{q}_3\left(\dot{q}_1, \ddot{q}_1, q_1^{(3)}, q_1^{(4)}, q_2, \dot{q}_2, \ddot{q}_2, q_3, \dot{q}_3\right) \tag{19}$$

with derivatives of q_1 expressed in terms of $\ddot{z}$ and its higher derivatives, all of which can be expressed as a function of the assumed bank maneuver, ϕ.

3.3.2 Case II: Drive Algorithm for Semicircular Critical Perception

The lower partition of matrix J_v of equation 10 is not singular, which suggests it is possible to express device angular accelerations $\ddot{q}_1$ as function of aircraft angular accelerations. A drive algorithm can be constructed using this inverse that would be appropriate if it were desired to produce angular acceleration *onset* cues that matched those of the aircraft. The device would function similar to the Stewart platform in that it would provide onset angular acceleration cues (but not rectilinear ones) that would precisely match those of the aircraft. There would be no angular artifacts. However, the magnitude and direction of the sensed g-vector would be dictated by the commands to achieve angular acceleration fidelity, thus failing to emulate the rectilinear accelerations of the aircraft and creating rectilinear artifacts. These artifacts are not present in the Stewart platform.

Another algorithm is presented here, that can be used to produce the *continuous* angular velocity cues that can lead to spatial disorientation by confusing the senses of the semicircular canals. For a bank maneuver, the rotary device (i.e. the 3 DoF cascade device with a planetary arm length of zero), the following commands produce reasonable yaw and roll fidelity:

$$\dot{q}_1^{com} = K_{SD}\dot{\psi} \tag{20}$$

$$q_2^{com} = \pi / 2 \tag{21}$$

$$q_3^{com} = k_{cross}\phi \tag{22}$$

where K_{SD} and k_{cross} are constants that are used to tune the fidelity of the simulator. The maneuver variables on the right hand side of equations 20-22 can constructed from instantaneous output of a simulator's aircraft model, and, hence, can be used for a pilot-driven simulator. Since the drive algorithm does not utilize equation 15, derivatives of the joint variables in the kinematic model are computed directly from the maneuver variable ϕ.

3.3.3 Case III: Drive Algorithm for Mixed Otolith/Semicircular Critical Perception

It is possible to provide fidelity that is a combination of otolith and semicircular senses. The Case III objective is to provide elevated g-level cues in conjunction with high fidelity roll acceleration, using a drive with a finite length planetary arm L_2. Device joint (q_2) is locked in order to eliminate a pitch artifact, recognizing there will be a degradation in distribution of g-acceleration between components. It is a combination of Cases I and II:

$$\dot{q}_1^{com} \approx \sqrt[4]{(a_{mag} / L_2)^2 - (g / L_2)^2} \tag{23}$$

$$q_2^{com} = \pi / 2 \tag{24}$$

$$q_3^{com} = q_{3init} + k_{cross}\phi \tag{25}$$

where q_{3init} is the initial roll orientation of the platform as determined for the selected idle speed.

4 Results and Discussion

The results are presented for each of the three drive algorithms defined in the previous section, by comparing plots of the time history of selected components of aircraft acceleration with the corresponding motion system output. All of the drive algorithms are devised for the same kinematic configuration, the 3R cascade, and all results are for the same maneuver, transition into a coordinated turn. In all cases, the model starts with the aircraft flying straight-and-level. Initial conditions of the drive and the vestibular system are set to the corresponding steady state values. In cases I and III, the simulator is spinning at the start at a specified idle speed that increases the simulator g-level above 1g. In figure 6 the initial simulator acceleration of 1.28g can be observed. In case II where $L_2 = 0$, idle speed has been set to zero, as can be seen in figure 8. All data presented here is in frame-v components so z-direction acceleration for level flight is negative. The data is also computed is anatomical coordinates.

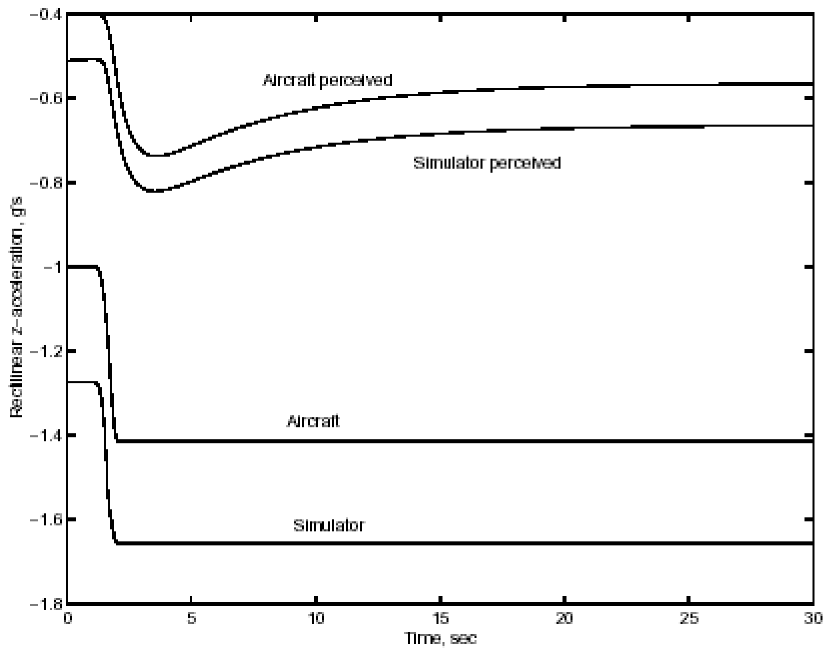

Figure 6: Comparison of aircraft and Case I simulator G_z acceleration for the sample maneuver.

In figure 6, the simulator acceleration is seen to have no delay in responding to the aircraft roll maneuver. This is because the kinematic model contains only the command to the drive, and excludes all of the dynamics of the motion system, motor delays and the error in the feedback control. Reference [9] describes a similar model configured with a dynamic module for analysis of response time. Also shown in figure 6 and several others that follow, is perceived motion as computed with a version of Young's vestibular model embedded in the kinematic model. Both the aircraft input and the simulator output are presented as perceived time histories. The perceived amplitude is 'efferent firing' level, so only relative amplitudes between perceived senses should be compared. The drop off in otolith perception in figure 6, when compared to the persistence of the actual simulator acceleration, G_z illustrates the accommodation characteristic of Young's model.

In figure 7, the simulator roll response is seen to have both magnitude and phase differences relative to the aircraft roll. The simulator roll response for the Case I algorithm, is that required to orient the platform so that the linear acceleration vector is entirely G_z. The delay in perceived response of the Semicircular canals is seen to be approximately 0.3 seconds.

Case II is shown in figures 8 to 11. Figures 8 and 9 are for the parameters $K_{SD} = 10$ and $k_{cross} = 0.5$. The simulator is seen to have roll response comparable in shape to that of the aircraft, but approximately one-half of the magnitude. The G_z acceleration becomes more positive (reduces) as the platform rolls, with G_y the component (not shown) becoming nonzero. This is the 'price' of attempting to attain roll fidelity with this device and this algorithm. Figures 10 and 11 shows that roll fidelity can be made precise by setting $k_{cross} = 1$, at the expense of even more loss in G_z fidelity.

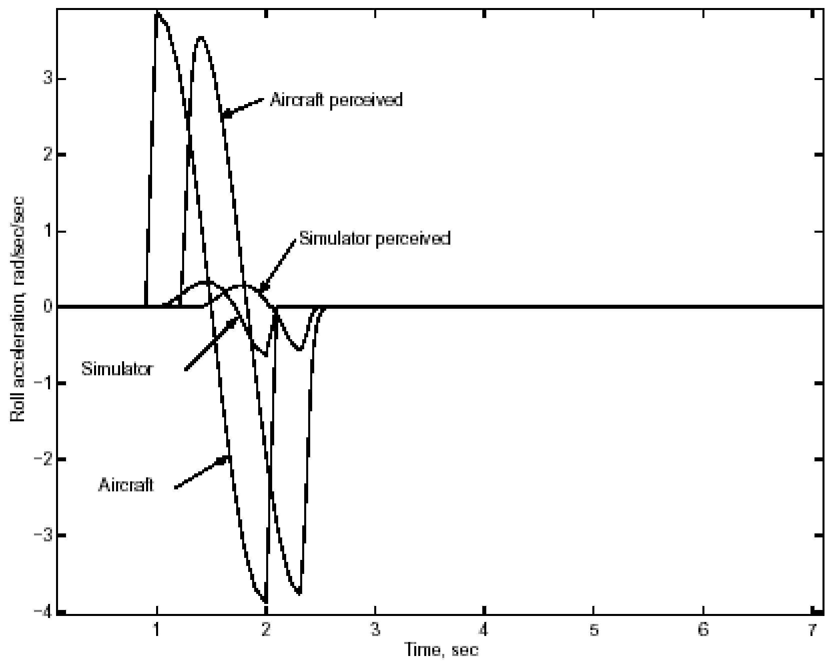

Figure 7: Comparison of aircraft and Case I simulator roll acceleration for the sample maneuver.

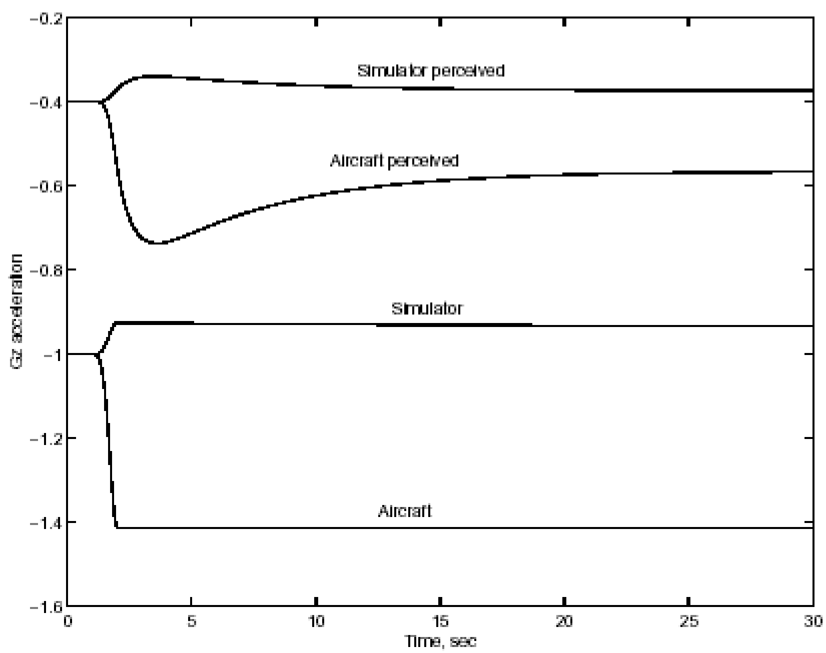

Figure 8: Comparison of aircraft and Case II simulator G_z acceleration for the sample maneuver with $k_{cross} = 0.5$.

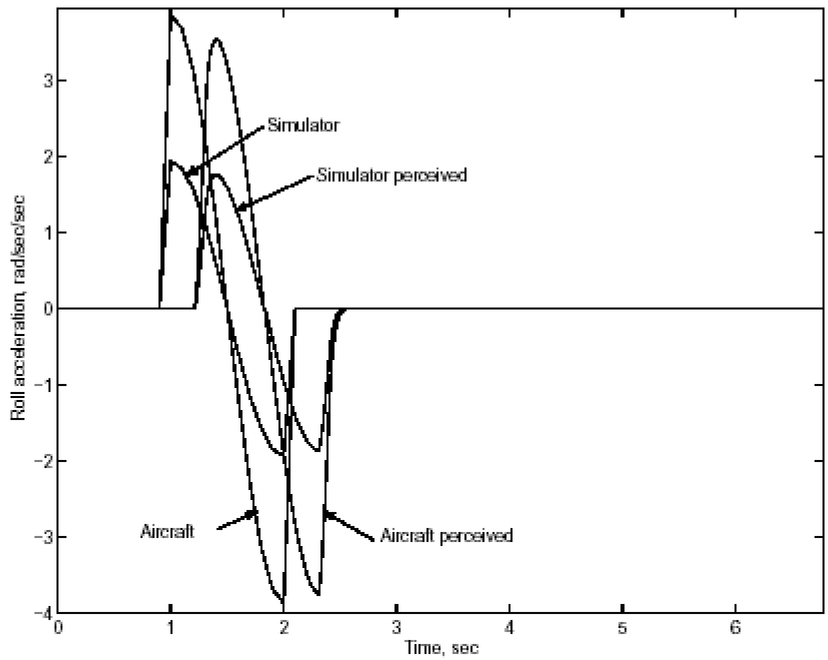

Figure 9: Comparison of aircraft and Case II simulator roll acceleration for the sample maneuver with $k_{cross} = 0.5$.

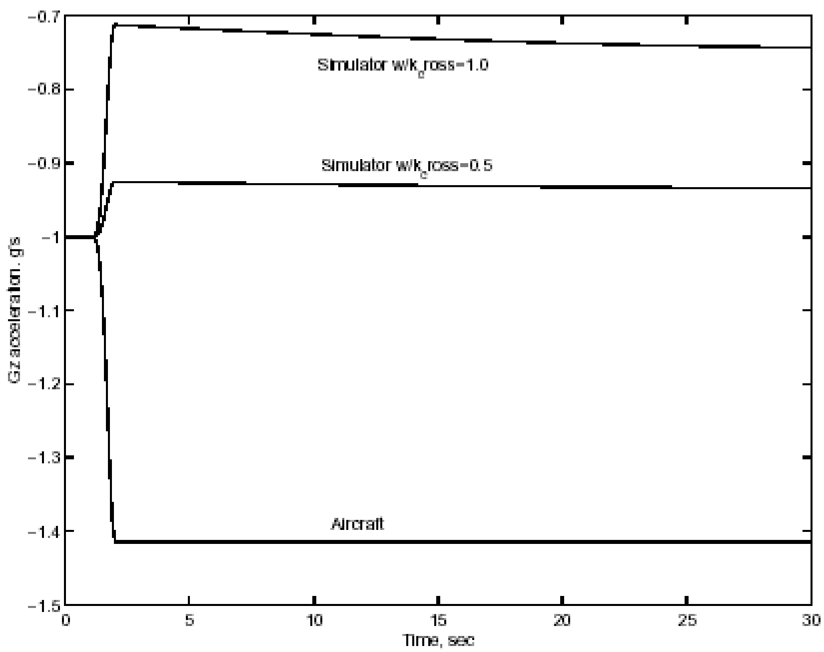

Figure 10: Comparison of aircraft and Case II simulator G_z acceleration for the sample maneuver with k_{cross} parameterized.

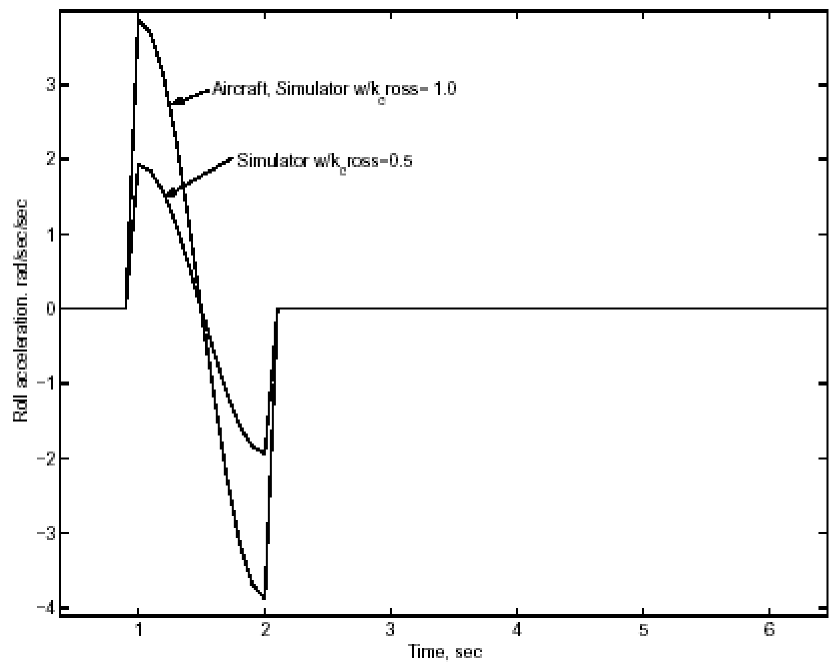

Figure 11: Comparison of aircraft and CASE II simulator roll acceleration for the sample maneuver with k_{cross} parameterized.

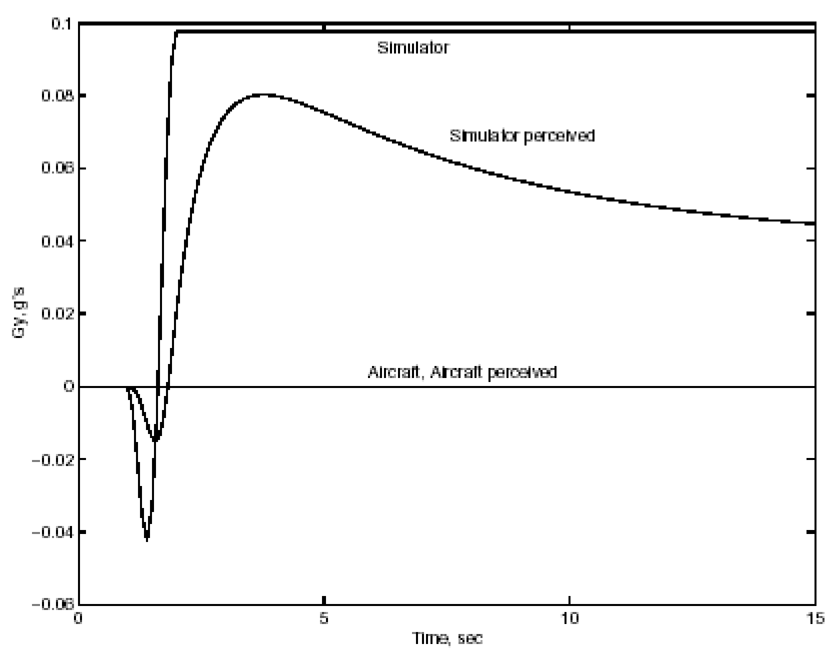

Figure 12: Comparison of aircraft and Case III simulator G_y acceleration for the sample maneuver.

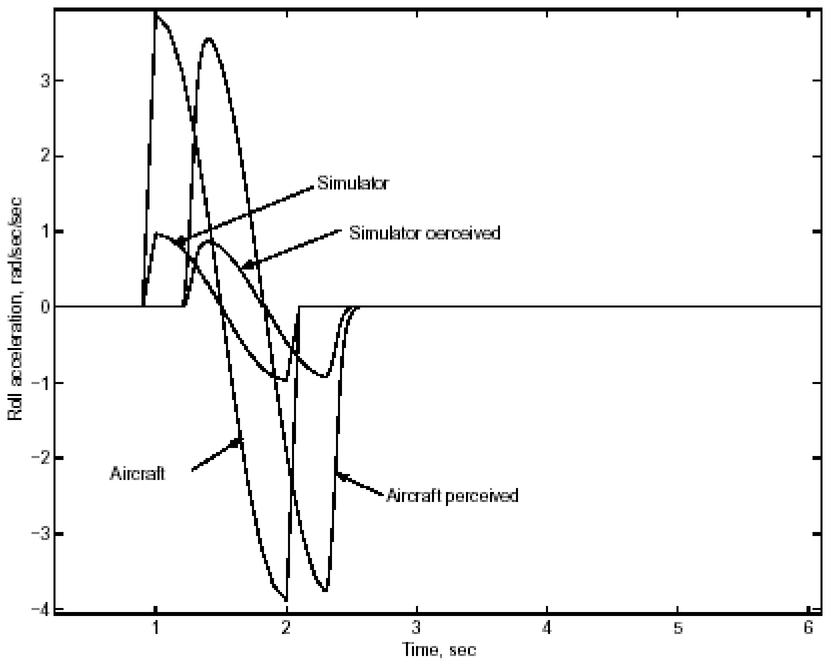

Figure 13: Comparison of aircraft and Case III simulator roll acceleration for the sample maneuver.

Case III is illustrated in figures 12 and 13 with $k_{cross} = 0.25$. The simulator is seen to have roll response comparable in shape to that of the aircraft, but approximately one-fourth of the magnitude. There is a $G_y \approx 0.1$ artifact created. G_z is comparable in shape and magnitude to that of figure 6.

It is noted that very little device specific data was required to obtain these comparative results. Depending on ones point of view, the performance of this R-R-R cascade drive and these drive algorithms might be considered adequate or appalling. None of the algorithms that have been compared here precisely match all aircraft accelerations. On the other hand, how much artifact is too much is not a well-defined. Recent tests by Chelette [9], for example, have shown that very high angular accelerations are perceived as only slightly disturbing. Further, the range of application of a device strongly influences how much artifact is produced. There are no motion simulators currently marketed that are capable of producing both transient and sustained 6 DoF response of full flight and there probably never will be since that would entail flying the simulator. There are, however, devices currently marketed that are highly capable for specific applications such as producing spatial illusions. An open question is whether additional aircraft response can be implemented in motion simulators that would enhance pilot training through economy and reduction in risk to life.

Options to be explored are: 1) identification of improved algorithms for existing drive configurations, 2) identification of new drive configurations and drive algorithms that would extend and improve on the capability of existing devices, and 3) identification of a highly redundant drive configuration and set of drive algorithms that could provide general purpose training, perhaps by changing algorithms 'on-the-fly' in response to flight conditions derived from the simulator's aircraft model. The kinematic/dynamic model being developed by the authors seems to be a useful tool for predicting the performance obtained these options as well as for other applications such as establishing quantitative requirements for motion simulators. The kinematic model requires minimal characterization of the drive device. The dynamic model requires a rather detailed set of drive system parameters. Both models would appear to be useful as design and assessment tools prior to the more costly and time consuming step of prototype development.

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Use of Simulator Spatial Disorientation Awareness Training Scenarios by the U.S. Army and National Guard

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Summary

Every year the U.S. Army loses aviation assets due to spatial disorientation (SD). All aircrew members, regardless of flight experience, are vulnerable to SD. Despite academic training and new technologies, SD accident rates are not improving. In 1997, the United States Army Aeromedical Research Laboratory (USAARL) developed a method of simulator training to provide experience with factors leading to potentially disorienting events. Actual SD accident summaries were reviewed and those accidents which could reasonably be replicated in a visual flight simulator were selected for the training scenarios. The published scenarios were distributed and were available for use by units on a voluntary basis for three years. Although touted as excellent by Army aviation leaders, this training is not required at any aviator training level. The primary purpose of the study was to determine the extent to which the USAARL SD awareness scenarios are used and are thought to benefit those receiving the training, and whether there is a desire to make the scenarios mandatory in aviators' annual simulator training requirements. A survey evaluating aviator SD experiences, and knowledge, use and opinions of the scenarios was distributed to U.S. Army/National Guard (NG) aviation units worldwide. The responses were used to produce descriptive statistics to determine relationships between flight experience levels and SD experience, experience levels/duty positions and exposure to SD scenario training, and to ultimately determine the level of acceptance of the USAARL SD awareness scenarios in the U.S. Army/NG. The findings revealed that the National Guard has been more aggressive in its voluntary integration of this training than the active Army. A majority of the sample having experience with the USAARL SD awareness scenarios had a positive opinion of the training indicating that it has 1) better prepared them to recognize factors which make SD more likely, 2) improved decision-making skills, 3) improved overall situational awareness and crew coordination skills, and that 4) all aviators would benefit from the training. With the apparent support for such training, aviation leaders could implement a training program with minimal effort. The research revealed that the majority of U.S. Army/NG aggregate has not been trained using the simulator scenarios. Apparently, without specific guidance and a regulatory requirement, simulator SD awareness training will not be conducted extensively. Without active advocation, what appears to be an effective means to mitigate the SD hazard will continue to be overlooked, and SD will continue to take its toll on the aviation community.

Introduction

Spatial disorientation occurs ". . . when the aviator fails to sense correctly the position, motion, or attitude of his aircraft or of himself within the fixed coordinate system provided by the surface of the earth and gravitational vertical" (Benson, 1978). SD remains an important source of attrition in military flying. U.S. Army Field Manual 3-04.301 (Headquarters, Department of the Army, 2000), Aeromedical Training for Flight Personnel, states that, "Spatial disorientation contributes more to aircraft accidents than any other physiological problem in flight." Regardless of their flight time or experience, all aircrew members are vulnerable to SD. According to the U.S. Army Safety Center (USASC) accident files and a report published

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by the U.S. Army Aeromedical Research Laboratory (Braithwaite et al., 1997), SD was considered to be a significant factor in 291 (30 percent) of Class A, B and C helicopter accidents in the U.S. Army between 1987 and 1995. According to the report, during this time, 110 lives were lost and a cost of nearly $468 million was incurred. The monetary cost of SD is high and the fatality rate is between one and one-half to two times that of nondisorientation accidents.

One of the means of reducing the impact of SD may be through enhanced awareness and training of aviators. While aviators may have had some experience in recovering from unusual attitudes during initial entry flight training, it is not possible to demonstrate many of the disorienting circumstances safely during actual flight. It can, however, be safely and effectively demonstrated in a visual flight simulator.

Simulator flight scenarios were developed (Estrada et al., 1998) in support of a USAARL research protocol for the assessment of using simulated spatial disorientation scenarios in training U.S. Army aviators. Actual SD accident summaries from the USASC were reviewed and those accidents which could reasonably be replicated in a visual flight simulator were selected for the development of the simulator scenarios.

A study was then conducted to assess the feasibility of using visual flight simulator scenarios to train aviators to recognize, avoid, and overcome SD. The study, completed in 1997 and published as USAARL Report No. 2000-06, revealed the potential benefits of utilizing helicopter visual flight simulators in the process of increasing pilot awareness of the hazards of SD. The research data collected indicated a very favorable response to this method of training. The result was that aviators receiving the SD scenario training increased their situational awareness of the conditions and events that lead to SD. In addition, the scenarios provided training to assist aviators in overcoming SD once it was encountered. Other, yet equal, benefits from this method of training were found to be the reinforcement of aircrew coordination and the development of decision-making, risk assessment, and judgement skills.

Background

The collection of simulator training scenarios was published as USAARL Report No. 98-17 in January of 1998. Following its publication, the report was, and continues to be, widely distributed and has been positively received by the aviation training community. Currently, the scenarios are touted to the attendees of the U.S. Army Aviation Center's Aviation Division Commander's Course and the Brigade/Battalion Pre-Command Course to demonstrate to future aviation commanders the accident prevention potential of such simulated training. Presently, the Eastern Army National Guard Aviation Training Site (EAATS) mandates, by standing operating procedures (SOPs), training in the use of the USAARL-developed scenarios. The Western Army National Guard Aviation Training Site (WAATS) uses the scenarios during aviator refresher training. The active army, however, has chosen to promote the scenarios on a voluntary basis only, leaving their use to the discretion of the unit commander or unit instructor pilots.

In a presentation at the November 2000, "Recent Trends in Spatial Disorientation Research" Conference, held in San Antonio, Texas, a USAARL research psychologist stated that the preliminary results of a review of SD accidents for fiscal years (FY) 1996 through 2000 are similar to the reviews by Durnford et al. (1995) and Braithwaite et al. (1997). It was further stated that data comparison with FY's 1991 through 1995 showed that the SD accident rate is not decreasing, and if anything, since 1995, has slowly started increasing. This trend indicates that despite the best efforts of the USASC to educate the aviator through printed accident reviews and the efforts of the developers of better aircraft orienting technology (cockpit head-up displays, improved night vision devices, global positioning navigation systems, etc.), there has been little change in the SD accident rate.

Current study

The purpose of this study was to determine the demographics of Army aviators and civilian simulator instructor/operators who use, have used, or do not use the USAARL SD awareness training scenarios as part of their annual simulator training requirements. Particular emphasis was placed on whether the SD awareness training scenarios, after having been available for use by U.S. Army and National Guard aviation units for three years, actually have been used by units to improve their aviators' ability to recognize those factors that lead to spatially disorienting situations. Another goal was to determine, in the opinion of the aviators and civilian simulator instructor/operators who have used them, whether the scenarios have improved their crew coordination skills and increased their general situational awareness.

The following research question is addressed in this study: In the opinion of Army aviators and civilian simulator instructor/operators, should simulator SD awareness training scenarios become a mandatory part of the U.S. Army Aircrew Training Program (ATP)? The outcome of the study could change the current Army simulator training requirements, making the use of SD awareness scenarios mandatory.

It is important to note that this study was limited to a percentage of the total U.S. Army and National Guard aviators and civilian simulator instructor/operators. The analysis of data, implications, conclusions, and recommendations resulting from this study were applicable only to the population from which the sample was taken (Hencshel, 2000).

The following assumptions were made: 1. It was assumed that the population of survey respondents was adequate to serve as a sample representation of all U.S. Army and National Guard aviators and civilian instructor/operators; 2. It was assumed that all personnel surveyed answered all of the survey questions honestly.

Definition of terms

The following terms are defined for clarity and understanding:

Aircrew Coordination: A set of principles, attitudes, procedures and techniques that transforms individuals into an effective crew (Headquarters, Department of the Army, 1996).

Aircrew Training Program: A program of individual and crew training established by an Army aviation unit commander which standardizes training and evaluation to ensure combat readiness.

Army Aviator: A qualified aviator who is a current member of the active Army or National Guard.

Civilian Instructor/Operator: A Department of the Army civilian (DAC) or civilian contractor employed as an instructor and/or operator of an aircraft simulator.

Class A accident: An Army accident in which the resulting total cost of property damage is $1,000,000 or more; an aircraft or missile is destroyed, missing, or abandoned; or an injury and/or occupational illness results in a fatality or permanent total disability (Headquarters, Department of the Army, 1994).

Class B accident: An Army accident in which the resulting total cost of property damage is $200,000 or more, but less than $1,000,000; an injury and/or occupational illness results in permanent partial disability, or when five or more personnel are hospitalized as inpatients as the result of a single occurrence (Headquarters, Department of the Army, 1994).

Class C accident: An Army accident in which the resulting total cost of property damage is $10,000 or more, but less than $200,000; a nonfatal injury that causes any loss of time from work beyond the day or shift on which it occurred; or a nonfatal occupational illness that causes loss of time from work (for example, 1 work day) or disability at any time (lost time case) (Headquarters, Department of the Army, 1994).

Flight Activity Categories (FAC): FAC's (1,2,3) are designated by a commander based on the proficiency required by a particular aviator in a specific job or position. FAC levels are significant in that they mandate a minimum annual simulator hourly requirement for an aviator (Headquarters, Department of the Army, 1996).

IMC (instrument meteorological conditions): Meteorological conditions expressed in terms of visibility whereas reference to aircraft instruments is required to maintain the aircraft's attitude, position and/or track.

Night (unaided): Condition of flight between official sunset and sunrise during which night vision goggles are not utilized.
NVG (night vision goggles): Condition of flight between official sunset and sunrise during which night vision goggles are utilized.
Readiness Levels (RL): RL's (1,2,3) are the levels of an aviator's proficiency to perform the unit's mission. An RL1 aviator is ready to perform a combat mission, whereas an RL3 has yet to demonstrate proficiency in basic flight tasks (Headquarters, Department of the Army, 1996).
Refresher Training: Training required by an aviator (RL3) if he or she has not flown within the previous 180 days or has failed to demonstrate proficiency in a basic (base) flight task (Headquarters, Department of the Army, 1996).
USAARL: The United States Army Aeromedical Research Laboratory conducts research to prevent or minimize health hazards in the military operational environment and to sustain the aviator's individual performance.
USAAVNC: The United States Army Aviation Center is responsible for training military, civilian and international personnel in aviation and leadership skills.
USASC: The United States Army Safety Center is responsible for conducting accident investigations on Class A and selected Class B aviation accidents. The Safety Center maintains a database of all Army accidents.
Visual Flight Simulator: A helicopter simulator with the capability to produce a moving, outside visual scene.
VMC (visual meteorological conditions): Meteorological conditions expressed in terms of visibility whereas reference to aircraft instruments is not required to maintain the aircraft's attitude, position and/or track.

Review of relevant literature and research

A search and review of international spatial disorientation awareness training literature and research revealed that visual flight simulators are not reportedly used to train aviators in SD awareness. In fact, all North Atlantic Treaty Organization (NATO) countries rely heavily on academic training and a ride in a rotating chair, commonly called the Barany chair, to increase their undergraduate aviators' awareness of the potential for SD during flight. According to NATO Standardization Agreement (STANAG) Number 3114, Aeromedical Training of Flight Personnel (1986), each NATO flight student will receive academic instruction of spatial orientation and disorientation, which "should be reinforced by a practical demonstration of the effects of vestibular stimulation using a rotating chair or suitable disorientation device to provide each student with a personal experience of some of the common illusions." For refresher and continuation training of graduate aviators, the STANAG requires a review of mechanisms underlying disorientation and of management of disorientation in flight. A discussion of recent incidents is then conducted.

Although the above-described syllabus is necessary and important, the training can be less than stimulating. For decades, aviators have received the same didactic instruction over and over again. In fact, an examination of the syllabus and student handout, Spatial Disorientation and Sensory Illusions of Flight, produced and used by the United States Army School of Aviation Medicine to train Army pilots is typical of any NATO SD awareness training program.

This lack of creativity and innovation in regards to SD awareness training was confirmed during the author's attendance of two international scientific symposiums: 1) NATO Research and Technology/Human Factors and Medicine Workshop on Aeromedical Aspects of Aircrew Training, San Diego, California (October 1998); and 2) Recent Trends in Spatial Disorientation Research, San Antonio, Texas (November 2000). The majority of the presentations clearly espoused advances in aircraft equipment technology to mitigate the SD problem.

To their credit, some countries' air forces have tried to improve their aeromedical training and have procured small motion-based flight trainers, which produce both visual and vestibular illusions in pilots. A tremendous improvement over the Barany chair, these devices spin or lean to "confuse" the aviator's orientation senses and thus provides a disorienting experience from which the pilot must recover. An example of such a device is the Environmental Tectonics Corporation's Gyro IPT (Leland, 1998). No presentation, however, with the exception of the author's, indicated that any other country or agency was using the visual flight simulator of a pilot's primary aircraft as an SD awareness trainer.

Current computer technology has allowed some ingenious "repackaging" of the same aeromedical physiological training and turned it into an interactive experience. In a paper by Folio (2001), a Compact Disc-Read only Memory (CD-ROM) is described as a "method of consistently training across the whole spectrum of aviators." The CD-ROM, Spatial Disorientation Training Module for Aviators, includes imbedded videos that help convey important points and mnemonics that help pilots remember lists of information.

In another clever innovation, O'Donnell et al. (1999), of NTI, Incorporated, developed a low-cost, desktop flight simulator. Using a realistic aerodynamic flight model and embedding situational awareness measures, the program, termed the Situation Awareness Flight Training Evaluator (SAFTE), is used to assess an aviator's situational awareness, including spatial orientation, during the conduct of an entire simulated mission. Although a useful training and research tool, its applicability to the rotary wing environment is limited since the program is intended for use by high-performance fixed wing pilots.

Cheung (1998) describes and proposes an SD awareness training most similar to the USAARL-developed scenarios in a Canadian publication Recommendations to Enhance Spatial Disorientation Training for the Canadian Forces. In it, he writes:

> The Canadian Forces should examine the benefits of incorporation of SD training into present and future flight training simulators . . . Specific scenarios derived from accident sequences would be valuable for the student to obtain direct experience in preventing and overcoming SD in a realistic environment.

Therefore, SD awareness training, by using a visual flight simulator to replicate the conditions under which an actual SD accident occurred, appears to be unique to the USAARL-developed scenarios. The scenarios, as stated previously, were assessed as to their viability as a training method (Johnson et al., 1999). A review of the general findings will be useful.

In the study by Johnson et al., the scenarios were presented in a UH-60 visual flight simulator to 30 experienced aviators who completed subjective questionnaire evaluations after each scenario and finally, an overall evaluation. According to the report, the results showed "a high level of acceptance of this training tool by a group of experienced aviators with differing backgrounds." All answers to the questionnaire were positive and when asked at the end of the survey to add any further comments on the scenarios, the comments included:

> "This training should be added to all Army aviation training programs."
> "Excellent training."
> "Extremely realistic."
> ". . . should be implemented into the initial entry rotary-wing training . . . ."

And finally, Johnson et al. reported that the study demonstrated the potential benefit of utilizing helicopter flight simulators in the process of increasing pilot awareness of the hazards of SD. The scenarios are believed to be an effective training tool and were shown to be compelling and relevant.

Methods

Survey population

The survey population was a representative cross section of military personnel (active duty, reserve component and National Guard), DACs, and civilian contract simulator instructor/operators. The population included line pilots, instructor pilots, standardization instructor pilots, unit trainers, aviation platoon leaders, aviation staff officers, aviation commanders, and maintenance test pilots.

Data collection

The survey instrument was developed and written by the first author. A copy of the instrument is at the Appendix. The instrument was distributed and administered by the author, or in his absence, by his appointed representative. Every attempt was made to distribute the survey instrument to various military installations and facilities in order to gather a representative body of data. For example, survey instruments were distributed at conferences and meetings that were attended by representatives from large installations such as Ft. Bragg, North Carolina; Fort Campbell, Kentucky; Fort Benning, Georgia; Korea and Germany. In addition, completed survey instruments were collected during pilots' meetings at the Eastern Army National Guard Training Site, Harrisburg, Pennsylvania, and Fort Rucker, Alabama. Both locations are meccas for student aviators from all over the country and the world representing units from the National Guard and the active Army.

Participation in the survey was entirely voluntary. Additionally, participants were anonymous except that their general duties/positions and flight experience levels were requested to establish population demographics.

Data analysis

The data from the survey instrument were used to produce descriptive statistics and were further analyzed using EXCEL Version 97. These data were used to determine significant links between experience levels and SD experience, experience levels/duty positions and exposure to SD scenario training, and to ultimately determine the level of acceptance of the USAARL-developed SD awareness scenarios in the U.S. Army/National Guard aviation community.

Results

The results are reported and organized into five general subject areas as depicted in Table 1.

Table 1.
General subject areas.

Survey Questions	Subject Area
1 - 6	Sample demographic and flight experience profile.
7 - 8	Sample experience with actual SD.
9 - 12	Sample experience with SD awareness training.
12 - 19	Sample experience with and opinion of USAARL SD awareness training and its effects.
20	Sample opinion of recommended simulator SD awareness training in the U.S. Army/National Guard.

A total of 175 surveys were distributed with 134 being fully completed and returned, providing a response rate of 77%. Although not addressed by the questionnaire, the author noted that 43 respondents, or 32.1% of the sample, were National Guard personnel, while 91 (67.9%) represented the active duty force.

Demographics and experience profile

Figure 1 illustrates the survey sample's current positions or job distributions.

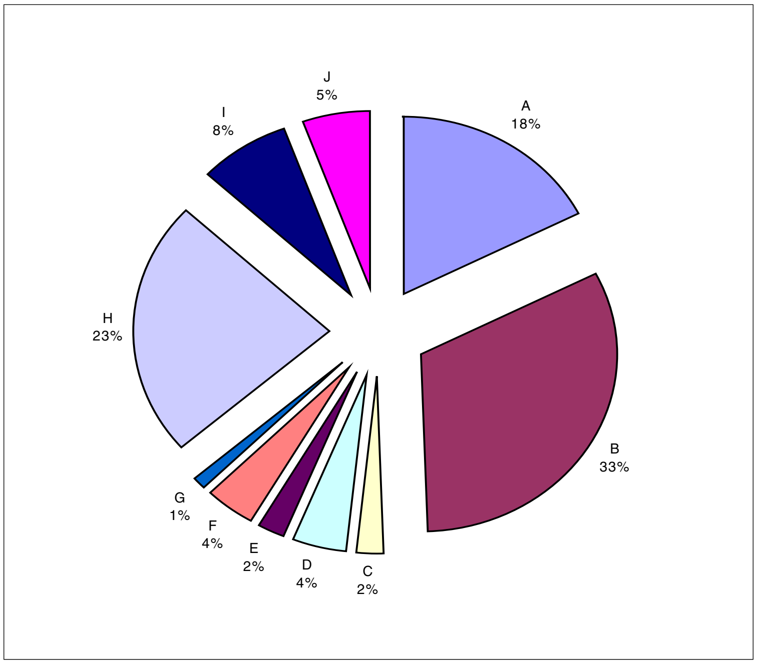

Figure 1. Positions/jobs distribution. A=line pilot, B=instructor pilot, C=aviation platoon leader, D=aviation company commander, E=aviation battalion commander or higher, F=Department of the Army civilian or civilian instructor operator, G=unit trainer, H=standardization instructor pilot, I=aviation staff officer, J=maintenance test pilot.

The results indicated that 91% had been pilots-in-command. Table 2 shows the distribution of Flight Activity Categories and Readiness Levels. (See Definition of Terms)

Table 2.
Distribution of FAC and RL.

	1	2	3	N/A	Totals
FAC	43 (32.1%)	75 (56.0%)	2 (1.5%)	14 (10.4%)	134 (100%)
RL	97 (72.4%)	7 (5.2%)	16 (11.9%)	14 (10.4%)	134 (100%)

The demography of total aircraft and simulated flight experience is presented in Figures 2 and 3, respectively. Total flight hours, aircraft and simulator, are usually reflective of an aviator's level of maturity, responsibility, and ability. Generally speaking, the greater the number of hours, the higher the pilot's capabilities. Note, also, that with more experience (flight hours) comes more exposure to flight conditions, making SD more likely to occur.

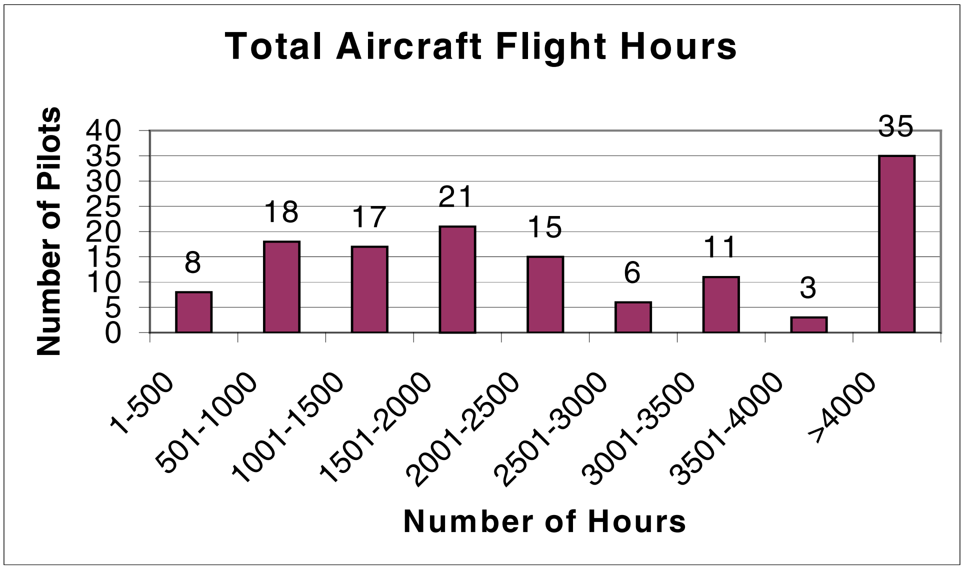

Figure 2. Total aircraft flight hours.

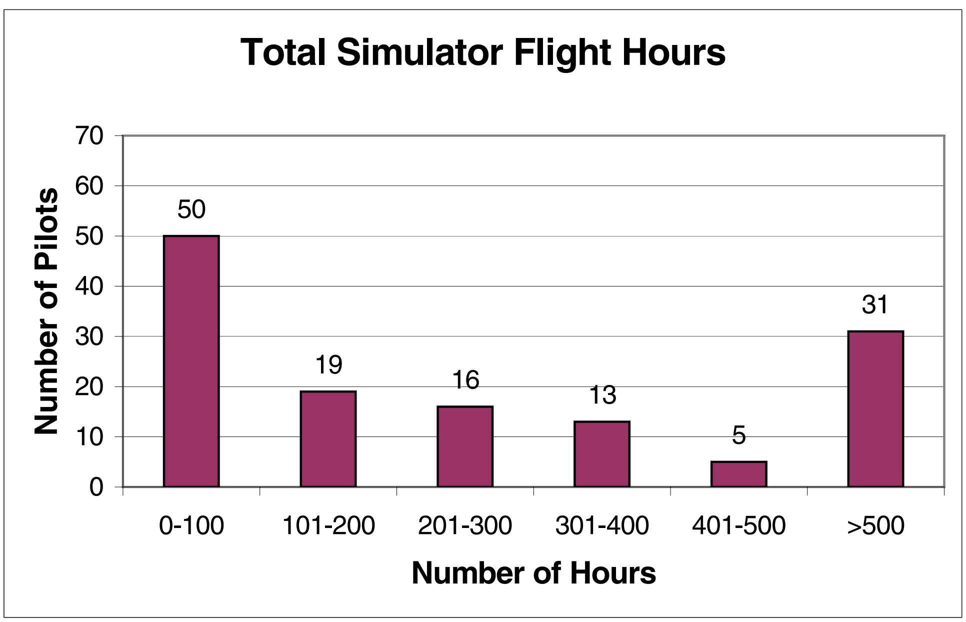

Figure 3. Total simulator flight hours.

Experience with actual SD

A review of the data revealed that 70.9% of the sample reported that they had had an SD experience in the actual aircraft. Those 95 respondents who answered positively to having had such an experience were asked to detail the experience(s) by providing the phase of flight, the number of times, and the flight mode during which it/they occurred. Table 3 provides the findings.

Table 3.
Reported SD experiences.

Phase of Flight	Of 95 Pilots, # Reporting	Of # Reporting Range of Times Reported	Number of Pilots Reporting in Flight Mode			
			Day	Night	NVG	IMC
Stationary Hover	24	1-20	5	10	16	3
Hovering Flight	21	1-20	4	8	14	2
Takeoff	14	1-25	3	3	3	11
Cruise Flight	60	1-20	10	14	9	48
Approach	23	1-20	3	7	7	14
Landing	22	1-20	8	5	18	2
Other (written in):						
External Load Pick-up	1	1	0	0	1	0
Aerobatic Flight	1	2	1	0	0	0
Operating in Snow	2	1-5	2	0	1	0
Traffic Pattern Turns	1	2	0	1	1	0
Climb from VMC into IMC	1	2	0	0	0	1

Figure 4 shows that as total flight time increases above 1000 hours, at least 71% of any given experience group has had at least one actual SD experience. Seventy-six percent of the entire sample reported having multiple SD events. An alarming finding is that 38% of the most inexperienced aviators (1-500 hours) had already experienced an SD event in their relatively short aviation careers.

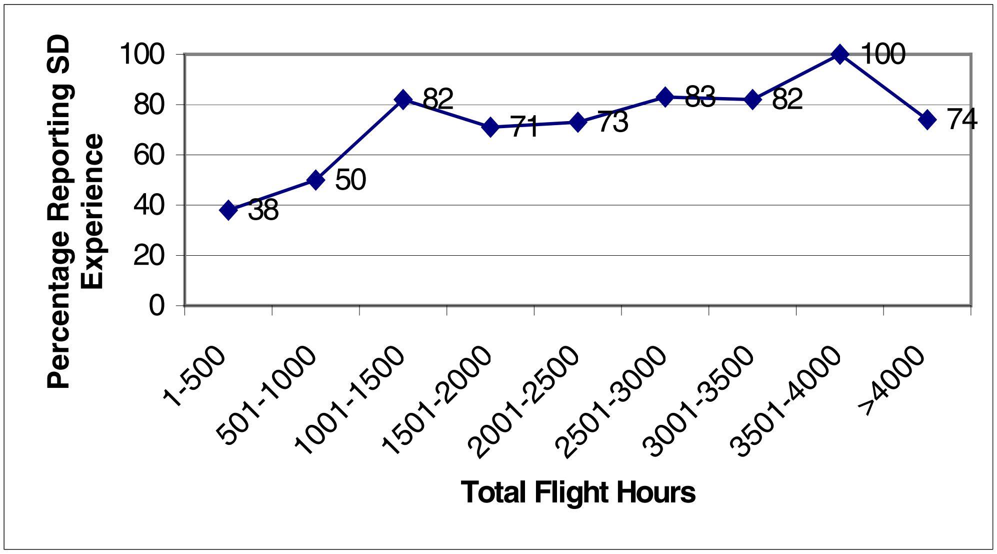

Figure 4. Percentage of reported SD experiences.

SD training experience

The next four questions of the survey instrument inquired as to the respondents' experience with SD awareness training in general.

The first question sought to establish the percentage of the sample that had ever heard of the USAARL SD Awareness Training Scenarios. Results showed that a slim majority (53%) had not heard of the scenarios. The data also indicated that although 75% of those having heard of the SD scenarios had also seen a demonstration, this number only reflected 35% of the entire sample. As for having received any manner of SD awareness/prevention training, 66, or 49%, responded yes. When all were asked if they had ever received or trained others using the USAARL Scenarios, only 30% answered yes. See Table 4 for additional results.

Table 4.
Aggregate SD training experience.

Survey Questions (abbreviated)	Yes	No
Ever heard of USAARL SD Awareness Training Scenarios?	63 (47%)	71 (53%)
Ever received a demonstration of USAARL SD Awareness Training Scenarios?	47 (35%)	87 (65%)
Ever received or trained others in any manner of SD training in a simulator?	66 (49%)	68 (51%)
Ever received or trained others using USAARL SD Awareness Training Scenarios?	40 (30%)	94 (70%)

Sub-sample comparisons

In order to more clearly examine and discern the field experience with SD training, the data collected were used to compare the Active Army with the National Guard. Table 5 illustrates this comparison.

Table 5.
Active duty/National Guard comparison.

Survey Questions (abbreviated)	Active Duty			National Guard		
	Yes	No	Don't Know	Yes	No	Don't Know
Ever heard of USAARL SD Awareness Training Scenarios?	38 (42%)	53 (58%)		25 (58%)	18 (42%)	
Ever received a demonstration of USAARL SD Awareness Training Scenarios?	26 (29%)	65 (71%)		21 (49%)	22 (51%)	
Ever received or trained others using USAARL SD Awareness Training Scenarios?	21 (23%)	70 (77%)		19 (44%)	24 (56%)	
Is using USAARL SD Awareness Training Scenarios mandatory in your unit?	1 (1%)	87 (96%)	3 (3%)	15 (35%)	27 (63%)	1 (2%)

In an attempt to determine the extent of the trainers' experience with SD training, the sub-sample data were further dissected and compared to produce Table 6. Note that the term "trainer" describes those reporting their current position/job title as instructor pilot, unit trainer, standardization instructor pilot, or DAC/Civilian Instructor/Operator. Note, also, that Table 6 displays only the percentages of "yes" responses of each sub-sample.

Table 6.
"Yes" response and percentages of sub-sample.

Military Component	Active Army		National Guard	
	Trainers	Others	Trainers	Others
Sample Size	55	36	24	19
Ever heard of USAARL SD Awareness Training Scenarios?	25 (45%)	13 (36%)	18 (75%)	7 (37%)
Ever received a demonstration of USAARL SD Awareness Training Scenarios?	16 (29%)	10 (28%)	15 (63%)	6 (32%)
Ever received or trained others using USAARL SD Awareness Training Scenarios?	13 (24%)	8 (22%)	14 (58%)	5 (26%)
Is using USAARL SD Awareness Training Scenarios mandatory in your unit?	0 (0%)	1 (3%)	10 (42%)	5 (26%)

Experience with USAARL SD awareness training

Of the 40 respondents who reportedly received or trained others using the USAARL SD Awareness Training Scenarios, 39 provided information regarding their experience with the training. (One individual did not answer Question 12 completely or Questions 13 through 19.)

Figure 4 indicates that 35, or 89.7%, of the sample regarded the training as necessary or higher, with a median rating of "Necessary and Interesting."

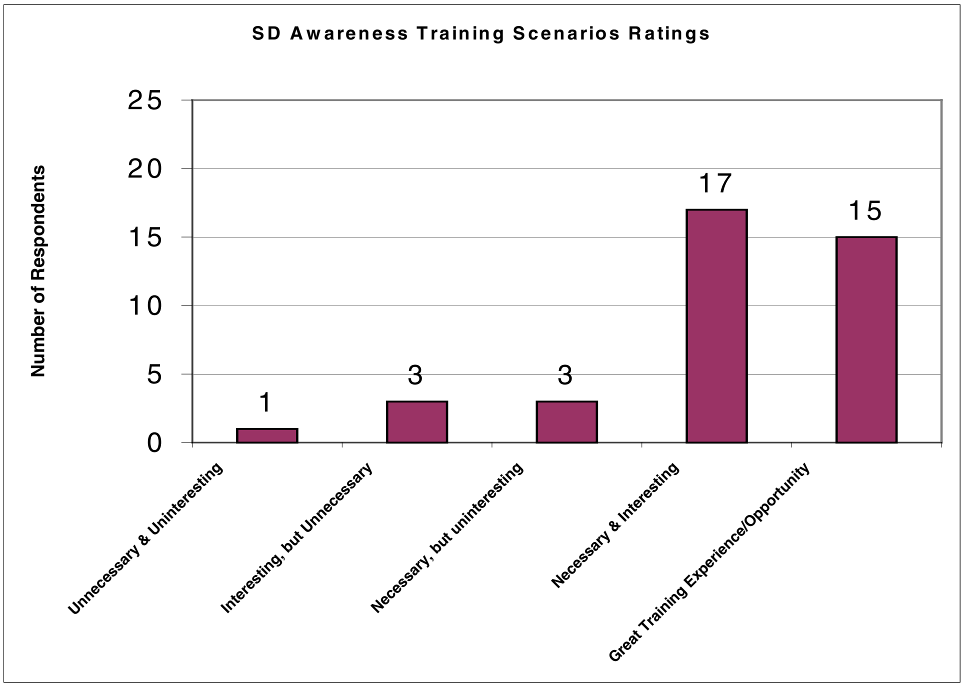

Figure 5. USAARL SD awareness training scenarios ratings.

USAARL SD awareness training scenario usage

Three questions were presented to determine the use and the use frequency of the USAARL SD Awareness Training Scenarios. When asked how many times they had received the training, over two-thirds (27) of the sub-sample indicated only once. As for using the scenarios to train others, 26 (67%) responded that they had used them (once to greater than 10 times) to train others. See Table 7 for the complete data distribution.

Table 7.
Frequency of use.

	Never	Once	Twice	3-5	6-10	>10
Number of times USAARL training was received.	N/A	27 (69%)	7 (18%)	3 (8%)	2 (5%)	0 (0%)
Number of times USAARL training was used to train others.	13 (33%)	7 (18%)	2 (5%)	4 (10%)	5 (13%)	8 (21%)

Mandatory use

In order to determine whether the training was performed on a voluntary basis or whether the unit's commander had required it, the sub-sample was asked if the use of the USAARL SD Awareness Training Scenarios was mandated by the unit's Aircrew Training Program. Forty-one percent said the training was mandatory, whereas 49% said the training was not mandated. Ten percent were not sure.

A look back at Table 5 (Active duty/National Guard comparison) shows a striking difference between the active force and the NG. Whereas 35% of the Guard reported that the training is mandatory in their units, only 1% of the active Army did.

Effectiveness

In addition to the above data, the respondents who reported experience with the USAARL scenarios were asked their opinions regarding the training's effectiveness and how, or if, it influenced or improved their flying awareness and communication skills (Table 8).

Table 8.
Assessment.

Opinion Survey Questions (abbreviated)	Yes	No	Not Sure	N/A
Did USAARL Scenarios training better prepare you to recognize factors which make SD more likely?	27 (69%)	5 (13%)	7 (18%)	0 (0%)
Did USAARL Scenarios training improve your ability to make better mission decisions?	26 (67%)	5 (13%)	8 (20%)	0 (0%)
Did USAARL Scenarios training improve your overall situational awareness?	28 (72%)	5 (13%)	6 (15%)	0 (0%)
Did USAARL Scenarios training improve your crew coordination skills?	28 (72%)	6 (15%)	5 (13%)	0 (0%)
Did USAARL Scenarios training actually prevent you from having an aircraft mishap/ accident?	3 (8%)	19 (49%)	17 (43%)	0 (0%)
Would all aviators benefit from being trained using the USAARL Scenarios?	35 (90%)	0 (0%)	4 (10%)	

Recommended SD Awareness Training

Finally, all respondents were asked if their annual simulator requirements should include some manner of SD awareness training and how often the training should occur. Ninety-seven of 134 individuals answered that simulator requirements should include SD awareness training, and the majority of those recommended that the training be conducted once annually, with an additional 48% recommending training frequency to be at least 2 times per year. See Figures 5 and 6.

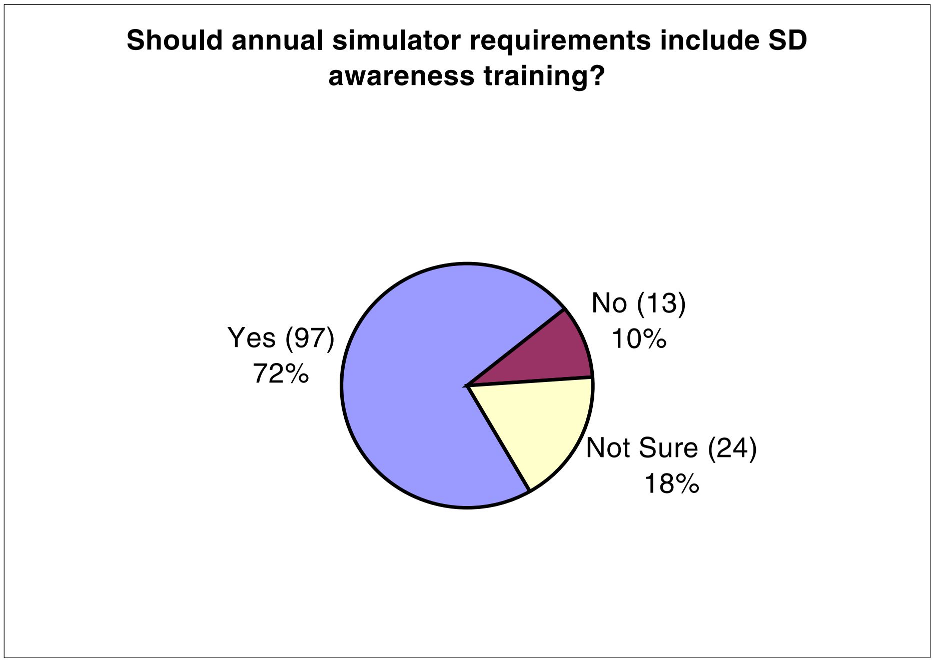

Figure 6. Simulator requirements and SD training.

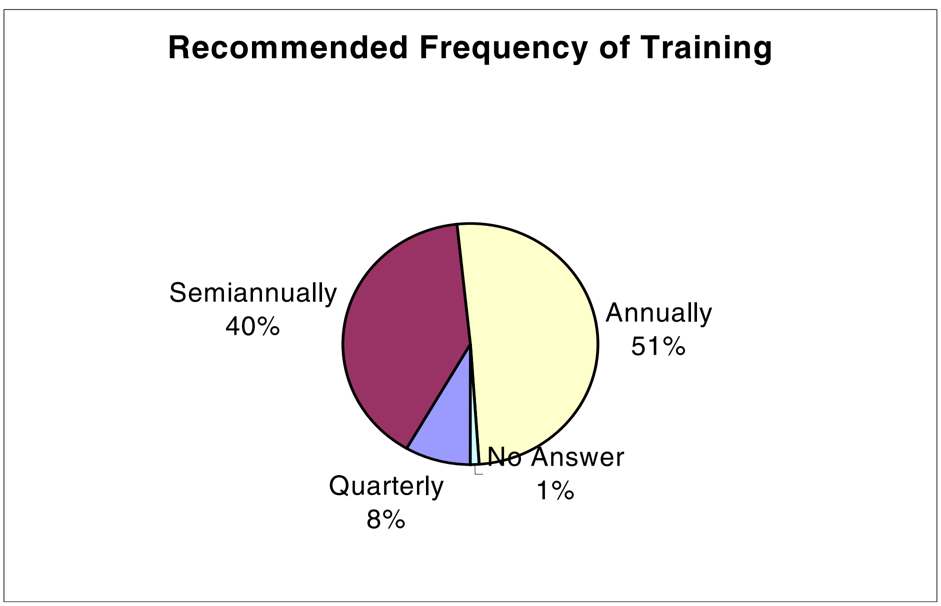

Figure 7. Recommended frequency of SD awareness training in a visual flight simulator.

Discussion

Demography

Although the respondents were anonymous and the surveys were distributed without regard to positions or jobs, a review of the data revealed that there was a large proportion of instructors and trainers who returned the surveys. In fact, even though the sample included representatives from all aviation positions and jobs, 61% were instructors and trainers. (This 61% of the sample was comprised of instructor pilots, standardization instructor pilots, civilian instructor/operators and unit trainers.) The fact that the surveys were distributed at two major Army aviation-training sites and that many of the surveys were distributed from various simulator facilities around the world where training is conducted may explain this concentration. Although this demography may not be statistically correct in representing the proportional population of the U.S. Army and National Guard, the large proportion of instructors and trainers returning the surveys was probably due to their interest and concern for training proposals and methods. An unintentional benefit of having a large instructor/trainer sample population is that the results are based on the comments and experience of those most qualified to assess a training program such as the USAARL SD Awareness Training Scenarios.

SD experience

Survey results indicate that a relationship exists between the amount of total flight time and those reporting SD experiences. As expected, as flight experience increases so do episodes of reported SD. The percentage of pilots reporting SD experiences increases sharply up to the 1500 hour experience level and appears to level off at approximately 80% for the remainder of their flying careers. These high percentages of reported SD events correlate with the high rates of SD accidents and mishaps referred to in the Introduction.

SD awareness training

Highly regarded, although not mandated, by USAAVNC leadership, the USAARL SD Awareness Training Scenarios are not receiving wide attention or use by the active force. The aggregate data (active Army and National Guard) retrieved from the questions relating to experiences with SD training (Table 4) demonstrated that the majority of the sample had not heard of or received training in the USAARL SD Awareness Training Scenarios. Keeping in mind that Army regulations do not require scenario training, the National Guard appears to be more committed to this training method. When the active duty Army is compared to the National Guard in Table 5, the Guard's enhanced commitment is clear. The survey indicates that 58% of the National Guard have heard of the training compared to only 42% of the active force. Whereas 23% of the active force have received the training, the Guard has trained an impressive 44%. In addition, only 1% of the active force reported that the scenarios were a mandatory part of their training, while 35% of the National Guard respondents said they were. After three years of promotion and availability, the USAAVNC leadership's strategy of marketing the training to aviation leaders for use on a voluntary basis appears to have been only minimally successful. Based on the data in Table 5, the Active Army has not integrated, and cannot be expected to integrate, the USAARL SD Awareness Training Scenarios into an active aviator's continuation training unless required to by regulation.

Arguably, the most important information collected from the survey may be that of the scenario training's effectiveness. According to the Instructor Pilot's Handbook (1991), in order for training to be successful, it must be purposeful, provide experience, and result in a change in behavior. Although a previous assessment, conducted in 1997 (USAARL Report No. 2000-06), proved that the USAARL scenarios, in a controlled study, were beneficial, effective, and well-received, their reception and appraisal by field units was unknown.

The results of this survey indicate that they were, indeed, deemed effective by the majority of those respondents with experience using the USAARL-developed scenarios. The following data reflect the majority's positive opinions of the training:

- Sixty-nine percent indicated that the training better prepared them to recognize those factors that made SD more likely.
- Sixty-seven percent indicated that the training improved their ability to make better mission decisions.
- Seventy-two percent indicated that the training improved their overall situational awareness and their air crew coordination skills.
- Three respondents felt that the training had actually prevented them from having an aircraft mishap/accident.
- Remarkably, 90% feel that all aviators would benefit from this training.

Finally, the collected information demonstrates that there is a desire by those in the field (72% of the sample) to have some manner of SD awareness training included in their annual simulator requirements. With the apparent support for such training, aviation leaders could implement a training program with minimal effort.

Conclusion

Spatial disorientation remains a formidable hazard to the U.S. Army aviation community. Based on the significant number of reported SD events, and if training is not improved, the Army aviator will have a real probability of becoming spatially disoriented in an actual aircraft during his/her aviation career. The preponderance of the sample population suggests that some form of simulator SD awareness training be developed. The research also revealed that despite USAAVNC promotion and demonstration to aviation leaders of the USAARL SD Awareness Training Scenarios, the majority of U.S. Army and National Guard aggregate have not been trained to recognize the factors which make SD more likely. Apparently, without specific guidance and a regulatory requirement, simulator SD awareness training will not be conducted on a voluntary basis.

Recommendations

Based on the conclusions achieved, this work recommends that aviation leaders mandate and regulate SD awareness training as part of an aviator's annual simulator requirement. An effective and proven method is by using the USAARL SD Awareness Training Scenarios as the basis of the program. The average USAARL SD Awareness Training Scenario takes approximately 10 minutes to perform and could be incorporated into an aviator's existing simulator training and annual hourly requirements. The training would be, in effect, transparent since no additional funds would be necessary.

Additional scenarios should be developed that target those phases of flight and flight modes identified in Table 3, such as cruise flight under instrument meteorological conditions, as being the most conducive to producing spatially disorienting effects.

As a final recommendation, aviators undergoing the U.S. Army's Instructor Pilots/Methods of Instruction (IPC/MOI) Courses should be qualified on the method of instruction and presentation of simulated SD awareness training scenarios. This would introduce this method of training to the instructor pilot, the one who would be in the best position to perpetuate and promulgate this type of training.

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Appendix

Survey instrument

United States Army Aeromedical Research Laboratory
Fort Rucker, Alabama

SPATIAL DISORIENTATION AWARENESS TRAINING SCENARIOS SURVEY

<u>Please circle the responses that most accurately answer the following questions.</u>

1. What term <u>best</u> describes your current position or job title.

Line Pilot — Unit Trainer

Instructor Pilot — Standardization Instructor Pilot

Aviation Platoon Leader — Aviation Staff Officer (any level)

Aviation Company Commander — Maintenance Test Pilot

Aviation Battalion Commander or above

Civilian (DAC or Contractor) Simulator Instructor/Operator (IO)

2. Are you currently or have you ever been a pilot-in-command (include limited PC duties)?

Y N NA

3. What is your current Flight Activity Category (FAC) designation?

1 2 3 NA

4. What is your current Readiness Level (RL)?

1 2 3 NA

5. How many <u>total</u> flight hours have you logged (exclude simulator)?

1-500 501-1000 1001-1500 1501-2000 2001-2500 2501-3000

3001-3500 3501-4000 4001 or greater

6. How many total visual flight simulator hours have you logged (exclude UH-1 simulator)?

0-100 101-200 201-300 301-400 401-500 501 or greater

7. To the best of your knowledge, have you ever experienced SD in the actual aircraft?

Y (Go to question 8) N (Skip question 8, go to question 9)

8. Yes, I have experienced SD under the following conditions:

Phase of Flight	Number of Times (If none, leave blank.)	Flight Mode (Circle all that apply)
At a stationary hover.		Day Night (unaided) NVG IMC
During hovering flight.		Day Night (unaided) NVG IMC
During takeoff.		Day Night (unaided) NVG IMC
During cruise flight.		Day Night (unaided) NVG IMC
During approach.		Day Night (unaided) NVG IMC
During landing.		Day Night (unaided) NVG IMC
Other: (Identify)		Day Night (unaided) NVG IMC

9. Previous to the pre-survey briefing, had you ever <u>heard</u> of the USAARL Spatial Disorientation Awareness Training Scenarios?

Y N

10. Have you ever received a demonstration of the USAARL Spatial Disorientation Awareness Training Scenarios?

Y N

11. Have you ever received or trained others in any manner of spatial disorientation awareness/prevention training in a visual flight simulator?

Y N

12. Have you ever received or trained others using the USAARL Spatial Disorientation Awareness Training Scenarios?

Y N (Go to question 20)

If yes, how would you rate the USAARL SD Awareness Training Scenarios?

1 = Unnecessary and uninteresting.

2 = Interesting, but unnecessary.

3 = Necessary, but uninteresting.

4 = Necessary and interesting.

5 = Great training experience/opportunity.

If yes, approximately how many times have you received the training?

Once Twice 3 to 5 5 to 10 Greater than 10

If yes, approximately how many times have you used the scenarios to train others?

Never Once Twice 3 to 5 5 to 10 Greater than 10

13. Is training using the USAARL SD Awareness Training Scenarios mandatory in your unit's Aircrew Training Program?

Y N Not Sure N/A (Civilian IO only)

14. In your opinion, did the USAARL SD Awareness Training Scenarios better prepare you to recognize those factors which make spatial disorientation more likely?

Y N Not Sure N/A (Civilian IO only)

15. In your opinion, did the USAARL SD Awareness Training Scenarios improve your ability to make better mission decisions during actual aircraft flight operations?

Y N Not Sure N/A (Civilian IO only)

16. In your opinion, did the USAARL SD Awareness Training Scenarios improve your overall situational awareness?

Y N Not Sure N/A (Civilian IO only)

17. In your opinion, did the USAARL SD Awareness Training Scenarios improve your crew coordination skills?

Y N Not Sure N/A (Civilian IO only)

18. In your opinion, do you believe that training received using the USAARL SD Awareness Training Scenarios actually prevented <u>you</u> from having an aircraft mishap/accident?

Y N Not Sure N/A (Civilian IO only)

19. In your opinion, do you believe that all aviators would benefit from being trained using the USAARL SD Awareness Training Scenarios and should receive the training?

Y N Not Sure

20. Do you believe that an aviator's annual simulator requirements should include some manner of SD Awareness Training?

Y N Not Sure

If yes, how often would you recommend SD Awareness Training in the simulator?

Once quarterly Once semiannually Once annually

THANK YOU FOR YOUR PARTICIPATION

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An Internal Validation of the British Army Spatial Disorientation Sortie

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SUMMARY:

Following didactic instruction, most aircrew are able to experience some of the disorienting illusions and limitations of the orientation senses in a variety of ground-based simulation devices such as the Barany chair. In order to reinforce instruction in spatial disorientation (SD) within the environment in which they operate, British Army Air Corps (AAC) helicopter pilots additionally receive an airborne demonstration of the limitations of their orientation senses during initial pilot training and as a quadrennial requirement post-graduation. The sortie syllabus has been previously described [1]. The objective of the assessment presented herein was to determine whether the SD demonstration sortie was a valid method for training aircrew in SD in the AAC. This paper records the results of an anonymous voluntary questionnaire completed by 265 experienced aviators and aviators in training over a two and a half year period immediately following the sortie. The results were entered into a relational database and evaluated by a disinterested party using standard descriptive statistics. The following conclusions were made: the manoeuvres performed in the SD demonstration sortie, and the sortie overall, were extremely effective at demonstrating the limitations of the orientation senses. Furthermore the aviators considered that the sortie greatly enhanced their overall awareness of SD. Thus we may conclude that the sortie satisfies the internal validation process of the Systems Approach to Training.

INTRODUCTION

Spatial disorientation (SD) occurs when a pilot fails to correctly perceive the position, motion, or attitude of his or her aircraft in relationship to the surface of the earth and the gravitational vertical. Such a misperception may have disastrous effects. SD was considered to be a significant factor in 291 (30 percent) Class A through Class C helicopter accidents in the U.S. Army in the 8-year period between 1987 and 1995 (Class A accidents are those exceeding $1 million or resulting in loss of life whereas Class C accidents are those exceeding $12 thousand) [2]. One hundred and ten lives were lost in these accidents, and a monetary cost of nearly $468 million was incurred. It should be remembered that only a relatively small proportion of SD episodes lead to accidents, and that non-mishap incidents also impose operational costs in terms of reduced efficiency or abandonment of the mission. In wartime, the extra pressure placed on the pilot's sensory and cognitive resources heightens the risk of SD. During Operation Desert Shield/Storm, 81 percent of U.S. Army aviation nighttime accidents were ascribed to SD [3].

One of the most important countermeasures to SD is the aviator's awareness of his physiological vulnerability to SD and the operational circumstances and phases of flight in which SD is most likely to occur. Consequently, all military aviators must attend courses of instruction in SD. Despite the regulations that mandate SD training (NATO STANAG 3114 and Air Standard 61/117/E), there is great variability in the quality, quantity, and frequency of this instruction, both between nations and services within a nation [4]. There is, therefore, room for improvement in all aspects of SD training. It has been long accepted that a demonstration of some of the illusions of SD and the limitations of the orientation senses during ground-based training is a vital part of the proper education of aviators. Most student pilots are given instruction during their flight training on how to overcome the effects of SD, but few air services provide a specific SD demonstration sortie to augment ground-based training.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

An in-flight demonstration of SD reinforces aircrew knowledge of the limitations of the orientation senses in flight and enhances aircrew awareness of potentially disorienting situations. In-flight SD training, on the other hand, consists of a series of flight procedures to teach aviators how to cope with disorientating circumstances and illusions (e.g., recovery from unusual attitudes during instrument flight). The teaching of recovery sequences is clearly the responsibility of the Qualified Helicopter Instructor (QHI) in both simulator and actual flying sorties, while an in-flight demonstration of SD, although it could be performed by specially trained QHIs, is best conducted by the Specialist or Consultant in Aviation Medicine (SAM or CAM) who, having performed the ground-based training, is on hand to explain the mechanics of SD. Currently in the AAC and in accordance with Joint Services Publication 318-20502, the SAM or CAM conducts SD training sorties during initial pilot training and on a quadrennial basis thereafter as a refresher.

It was in the pursuance of this philosophy that a specific SD demonstration sortie was developed and has been used by the British Army for over the last 18 years. The sortie demonstrates the limitations of their orientation senses to aviators during helicopter manoeuvres in flight. The demonstration cannot be conducted in a motion-based simulator such as the ASDD, which simulate SD in fixed wing aircraft relatively well, because such devices cannot create the appropriate rotary-wing acceleration environment to induce an effective result [5]. The British Army SD sortie has been previously described in detail, and its efficacy both in training aircrew and in preventing SD related accidents discussed [1].

In accordance with current British Army doctrine (Army Code 70670 PAM 4), the systems approach to training (SAT) requires organisations to monitor the efficacy and validity of training. Validation of training is the process of determining firstly, whether training is achieving specified training objectives (internal validation) and secondly, whether the training objectives reflect the requirements of “the job” (external validation). Continuous and systematic validation of training is necessary to establish that training is effective and to ensure that it is adjusted to meet changes in job requirements. Such changes may be caused by the introduction of new or modified equipment, by new techniques, or by the restructuring of the job to include new tasks or exclude old ones. Once the decision to train has been taken, consideration of the most cost-effective means of carrying out the training is necessary. Assessment of the effectiveness of training is a principal concern of trainers. Measures of efficiency on the other hand are the concern of others besides the trainer and are likely to involve consideration of factors beyond the competence of those immediately concerned with training. It must be stressed that this process is particularly important in the prevailing climate of fiscal constraint and limited resources.

Validation allows training programmes to meet changes in the job requirements. This is extremely important in aviation. Military rotary-wing aircraft are becoming more diverse and more sophisticated. In the military field, despite advances in control and instrument technology, the aircrew certainly do not have a lesser number of tasks, but these tasks have significantly changed in nature over the years. These tenets must drive the training requirement. As far as training in SD is concerned it is reasonable to make the following statements with respect to the SAT process: 1). The “job” may be generally defined as the optimal performance of the pilot in his duties, and specifically as the prevention and/or control of the hazard of SD, 2). Such is the nature of SD that aeromedical professionals may be concerned both with the delivery of training and the measurement of both its effectiveness and efficiency.

The metrics that may be used to determine the effectiveness of SD demonstration and training are both difficult to define and different studies have used different outcomes. There would be merit in standardising these aspects between services and nations. The extremes of those that have been used are from “user satisfaction to training” on the “soft end” of the spectrum, to a demonstrated reduction in the SD accident rate at the “hard” end. The former can be regarded as a measure of internal validation, whilst the latter goes much of the way to being an external validation assessment. However, even the latter is fraught with problems because of the differences in both the diagnosis (because there are often no witnesses to the catastrophic SD accident) and subsequent classification of the SD accident.

The only known type of SD training for which external validation has been applied is the rotary-wing SD demonstration sortie in the British Army. An objective analysis of this demonstration assessed the benefits in terms of operational outcome - its effect on lowering the SD accident rate in the AAC [6]. However, although we have reasonable external validation, no internal validation has recently been performed. This paper describes an internal validation assessment of the SD sortie by AAC personnel. During the study, the opportunity was also taken to gain subjective opinions on the current standard of SD training.

METHODS

In order to internally validate the current SD sortie demonstration, a research protocol was developed at The School of Army Aviation, Middle Wallop. The sortie was demonstrated to a cross section of Army aviators from the novice student to senior instructor pilots (hereafter referred to as participants). Two hundred and sixty five individuals experienced the sortie over a two and one half year period and gave their opinions via post-flight questionnaires. The Army personnel were from one of two groups: trained aviators and student pilots. All participants voluntarily agreed to the anonymous questionnaire.

In the British Army, the Consultant or Specialist in Aviation Medicine who is a pilot-physician both flies and conducts the sortie from a standardized syllabus [1]. The Gazelle helicopter was used in these demonstration sorties and was commanded and flown by a SAM or CAM from the pilot's seat. Participants (either two or three per sortie) occupied the cabin seats facing forward. They were fully briefed on the nature of the sortie, in particular, that the manoeuvres were not violent or nauseagenic; that the aim was to augment their ground training by demonstrating the limitations of perception; and that they were not being trained in how to overcome SD. Following a transit to the demonstration area, a series of forward flight and hover manoeuvres was conducted. In turn, each of the participants was asked to sit free of the airframe structures, note the aircraft's initial flight parameters, close their eyes, lower their dark visor (to limit cues from ambient sunlight), and, as the participant for that manoeuvre, give a running commentary on their perception of the aircraft's flight path. In this way, the participant (subject) was deprived of vision (the most important of the orientation senses) so that the limitations, particularly the unreliability of the non-visual orientation senses, could be demonstrated. The other participants (observers) were asked to observe but not comment until after the manoeuvre was complete. The SAM then debriefed the manoeuvre. All participants experienced at least one manoeuvre in each of the forward flight and hover groups as described below:

- **Level turn:**

Straight and level flight is established at 90 knots. After 10 seconds, a gently increasing (supra-threshold) roll to 30-degree angle of bank is commenced while maintaining airspeed and altitude. This is stabilized and, on completion of a turn between 180 degrees and 360 degrees, the aircraft is rolled wings level again at a supra-threshold rate. The subject is told to open his eyes once he considers that he is again straight and level. Debriefing points: the onset of the roll is normally detected, but as the semicircular canal response decays, a false sensation of a return to straight and level flight is perceived. As the roll to level flight is made, a sensation of turning in the opposite direction is perceived. The limitations of semicircular canal physiology are discussed.

- **Straight and level:**

Straight and level flight is established at 90 knots and one of the other participants is asked to close his eyes. The aircraft is flown with no alteration of altitude, heading, or airspeed. Debriefing points: because of small aircraft movements from turbulence and the aerodynamic response of the helicopter which stimulate the kinaesthetic and/or vestibular apparatus above their threshold, students perceive climb, descents, or turns in unpredictable and varying amounts. The erroneous sensations produced by brief stimulation of the kinaesthetic receptors and vestibular apparatus is discussed.

- **Straight and level deceleration to a free hover:**

Straight and level flight is established at 90 knots into wind, and once the subject closes his eyes, the helicopter is slowed within 30-40 seconds to a free air hover with no change of heading or altitude. Debriefing points: the nose-up pitch associated with the attitude change in the final stages of slowing the aircraft usually convinces the subject that a climb is taking place. In addition, a turn is often falsely perceived when balance variations are made to keep straight. The absence of accurate physiological perception of airspeed is discussed.

- **Inadvertent descent:**

This manoeuvre is commenced from about 500 ft above ground level (AGL). Straight and level flight is established at 90 knots, and the subject closes his eyes. While initiating a descent at below 500 feet per minute, a series of turns is commenced. When the aircraft is established in contour flight below 50 feet AGL, the subject is asked to report his heading, height, and airspeed and then open his eyes. Debriefing points: the descent is not usually perceived, and due to the proximity of the ground at the end of the manoeuvre, this demonstration forcibly and convincingly demonstrates the danger of inadvertent descent.

- **Hover:**

As the helicopter has a unique ability to accelerate about, as well as along orthogonal axes, the final series of demonstrations starts from a 5- or 6-foot hover. In turn, the participants are exposed to a variety of linear and rotational movements while maintaining hover height. The SAM keeps prompting the subject for a running commentary (to occupy channels of attention) and so exacerbates the onset of SD. Within these exercises, various manoeuvres are hidden so that when the subject opens his eyes, a dramatic end point is evident: climbing backwards at 10-15 knots; landing without the subject realizing it; a gentle transition to forward flight.

After the sortie, participants were asked to complete voluntary and anonymous questionnaires. Each questionnaire contained five questions requiring the participant to score each demonstration as either a subject or observer on a scale of 1-10 (1=extremely poor, 5=adequate, 10=extremely good). An additional question was asked, using the same scale, as to the participant's overall view of the sortie's effectiveness. Additionally, each participant was asked to determine how his or her individual awareness of SD had changed on a scale of 1-13 (1="I know nothing about SD", 7="No change", 13= "I am totally enlightened"). A final area was available for individuals to comment on the experience.

RESULTS

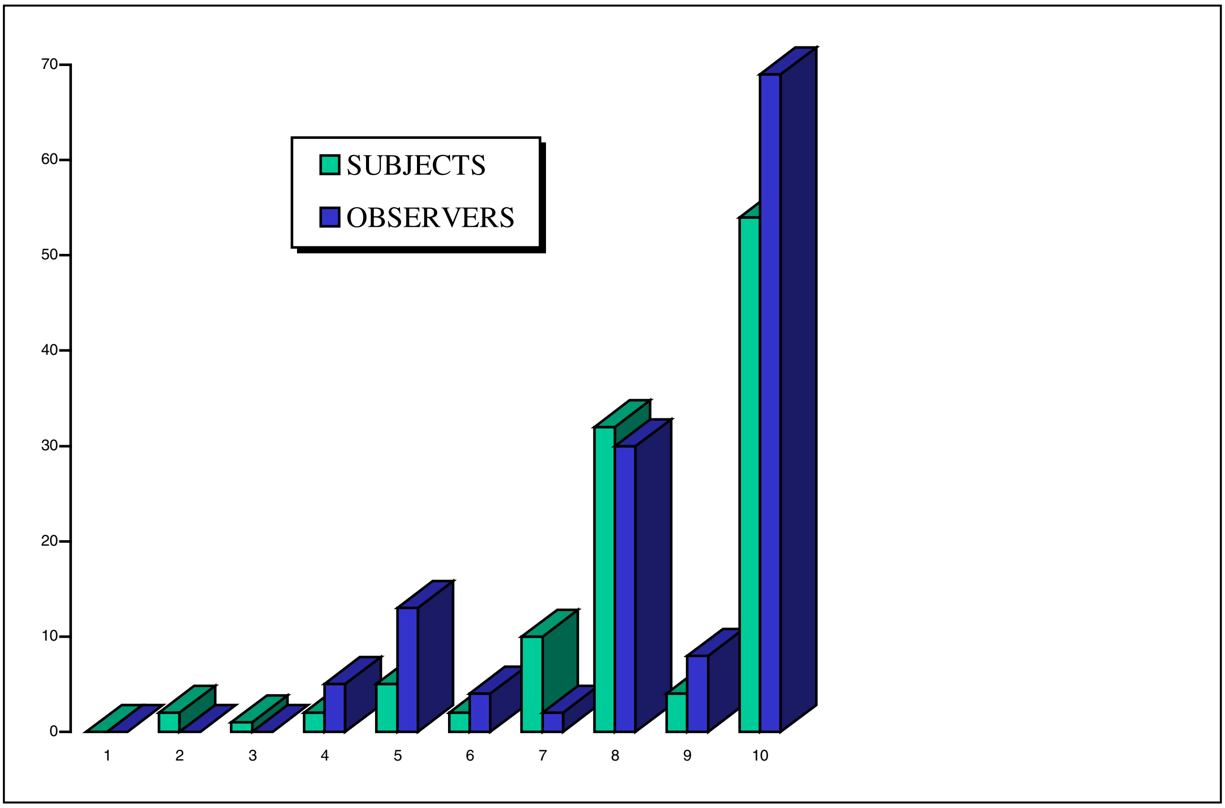
The results of this evaluation are based upon analysis of the post flight questionnaire data. Some additional comments from those experiencing the SD demonstration sortie are also recorded.

Assessment of the SD sortie manoeuvres

Participants were asked to rate each manoeuvre and the sortie overall, on its ability to convince them that their non-visual senses were unable to give them accurate orientation information. Out of the 265 questionnaires distributed, 265 were returned (100%). The student pilot participants numbered 167 (63%) while the refresher participants numbered 98 (37%).

The questions posed are reproduced in the figures annotated below together with some additional comments on the manoeuvres. The distribution of ratings for the individual manoeuvres and the sortie overall are presented in figures 1 to 7. All graphs represent combined data from the initial training participants and the refresher training participants, however, individual breakdowns are annotated in the legends accompanying each graph. Additionally, the total percentage of the subjects who felt that the demonstrations as well as the sortie *in toto* were at least adequate or better are annotated.

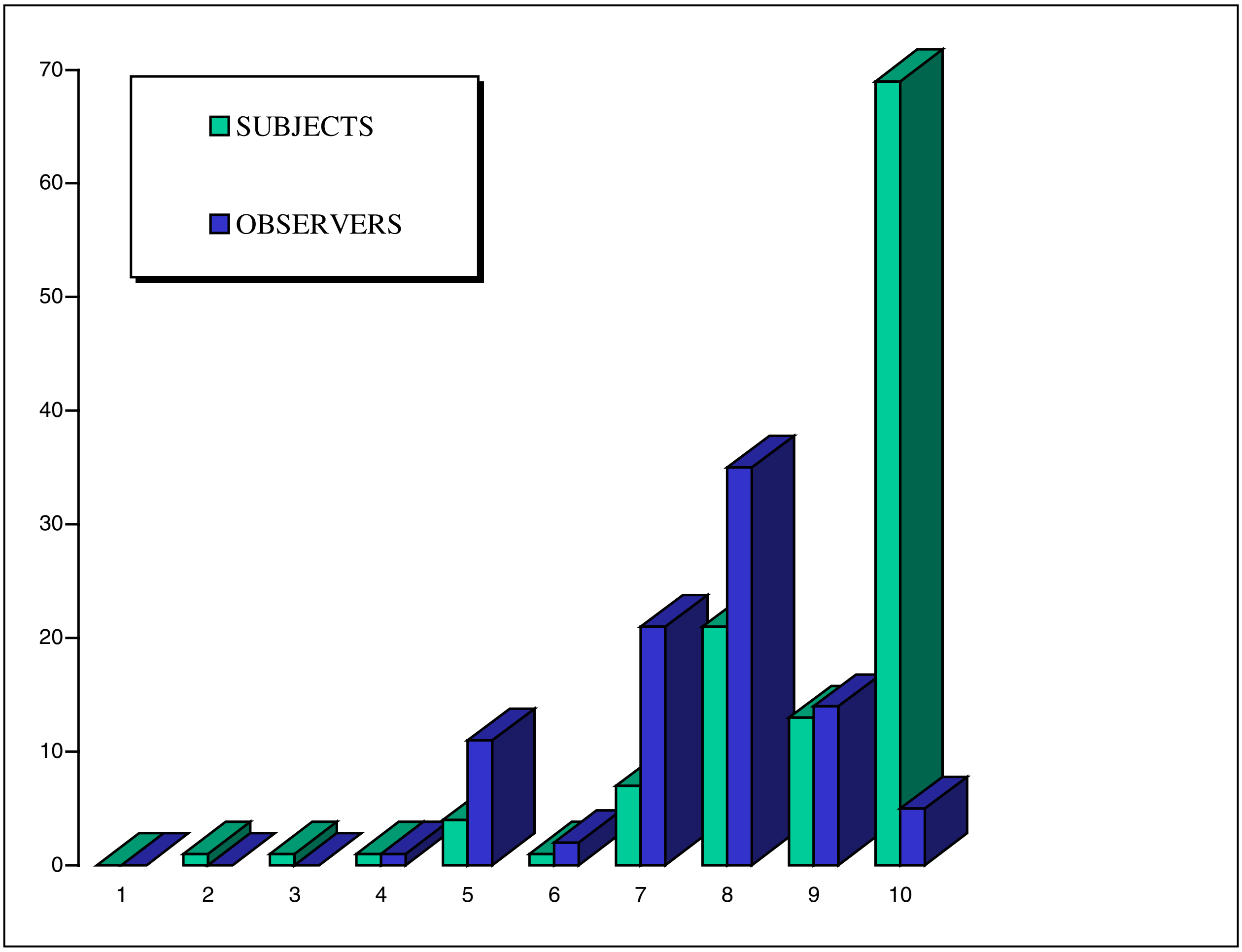
FIGURE 1: 360-DEGREE LEVEL TURN MANOEUVRE:



KEY: 1 = Extremely Poor 5 = Adequate 10 = Extremely Good			Break down of Initial **(I)** vs. Refresher **(R)** Participants			
COMBINED DATA						
STATISTICS	SUBJECTS	OBSERVERS	I SUB	I OBS	R SUB	R OBS
N=	112	149	69	98	43	51
Mean =	8.52	8.40	8.18	8.2	8.4	8.5
STDEV =	1.86	1.83	1.95	1.87	1.78	1.77
Median =	9	9	8	9	9	8
Mode =	10	10	10	10	10	10
Range	10-2	10-4	2-10	4-10	3-10	4-10
Question: "How successful would you rate the 360 degree level turn manoeuvre in its ability to convince you that it is difficult for you to sense motion and attitude without aircraft instruments?"						

Figure 1 demonstrates that of the 261 participants that experienced this manoeuvre, approximately 96% rated it as at least adequate in demonstrating SD and that greater than 89% of the participants rated it above average. Of note there was no statistical difference between the Initial and Refresher participants in their overall rating of the manoeuvre.

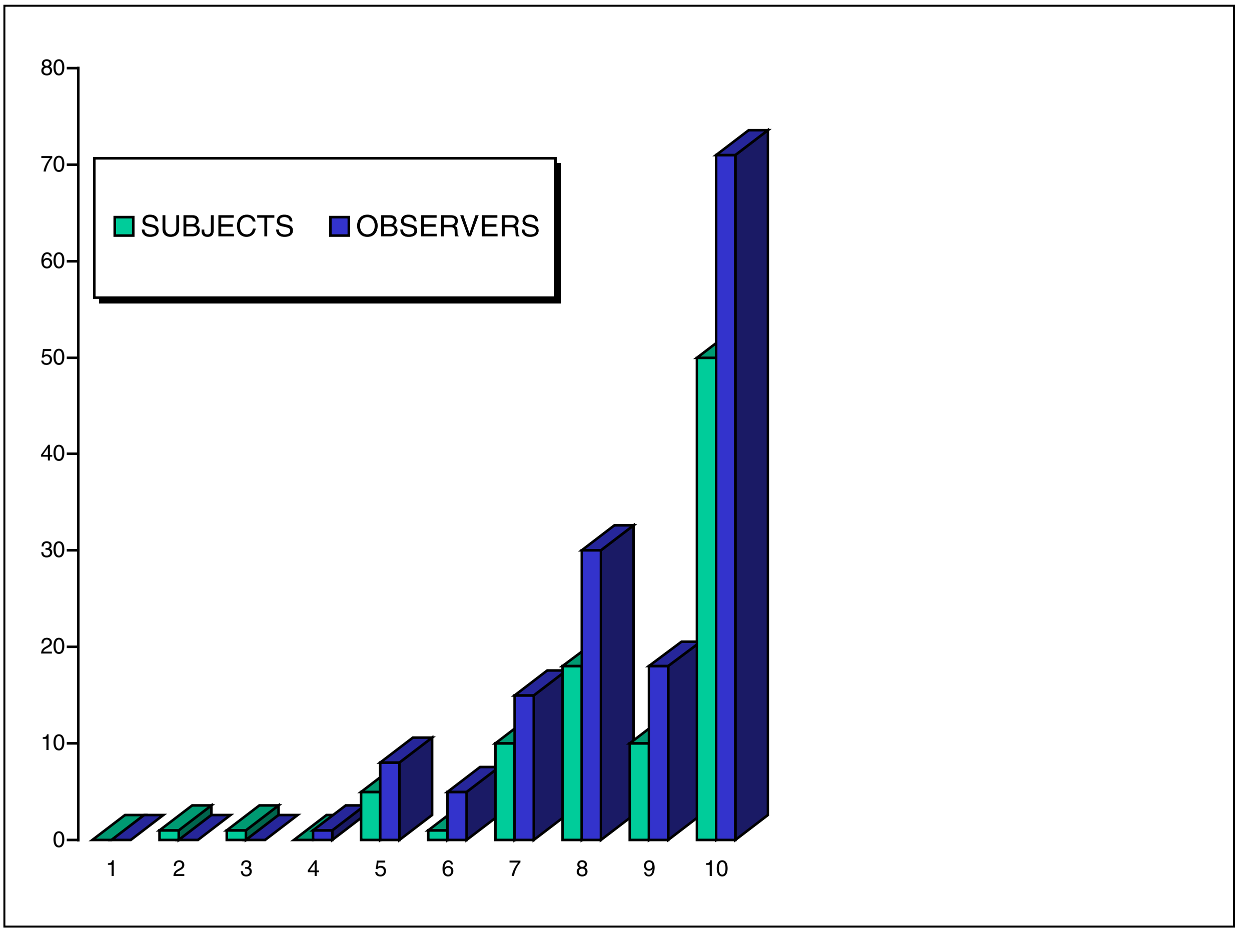
FIGURE 2: STRAIGHT AND LEVEL MANOEUVRE:



KEY: 1 = Extremely Poor 5 = Adequate 10 = Extremely Good			Break down of Initial **(I)** vs. Refresher **(R)** Participants			
COMBINED DATA						
STATISTICS	SUBJECTS	OBSERVERS	I SUB	I OBS	R SUB	R OBS
N=	117	143	68	100	49	43
Mean =	9.0	8.5	8.55	8.55	9.0	8.0
STDEV =	1.6	1.6	1.6	1.4	1.41	1.83
Median =	10	9	9	8	10	8
Mode =	10	8	10	8	10	8
Range	10-2	10-4	10-2	10-4	10-4	10-4
Question: "How successful would you rate the straight and level manoeuvre in its ability to convince you that random motion experienced in flight (e.g., turbulence) can give you the wrong information?"						

Figure 2 demonstrates that of the 260 participants that experienced this manoeuvre, approximately 98% rated it as at least adequate in demonstrating SD and that greater than 93% of the participants rated it above average. Of note there was no statistical difference between the Initial and Refresher participants in their overall rating of the manoeuvre.

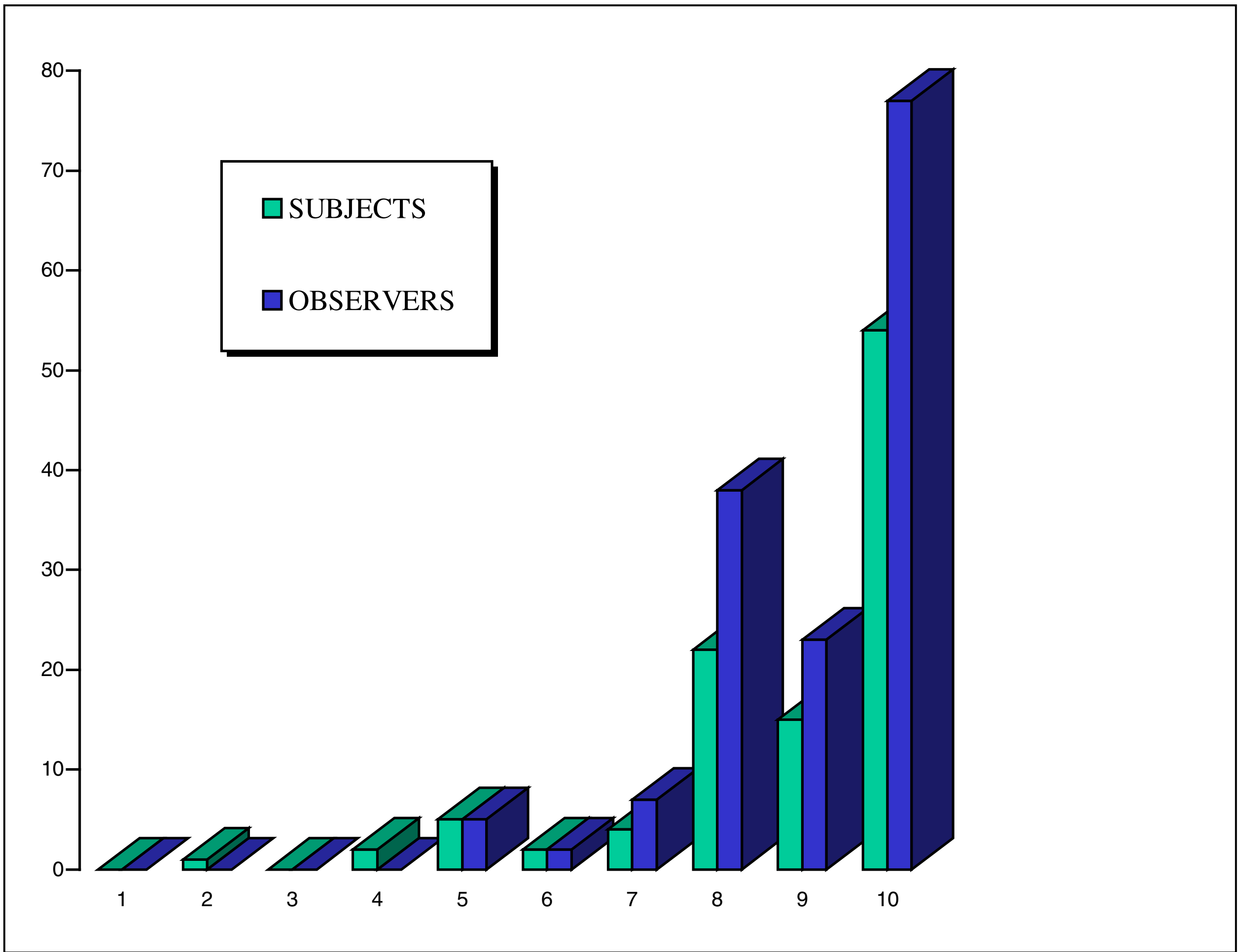
FIGURE 3: DECELERATION TO A FREE AIR HOVER MANOEUVRE:



KEY: 1 = Extremely Poor 5 = Adequate 10 = Extremely Good			Break down of Initial (**I**) vs. Refresher (**R**) Participants			
COMBINED DATA						
STATISTICS	SUBJECTS	OBSERVERS	I SUB	I OBS	R SUB	R OBS
N=	97	147	63	105	34	42
Mean =	8.71	8.76	8.8	8.5	8.7	8.6
STDEV =	1.75	1.50	1.53	1.47	1.8	1.5
Median =	10	9	9	9	9	9
Mode =	10	10	10	10	10	10
Range	10-2	10-4	10-2	10-5	10-4	10-5
Question: "How successful would you rate the deceleration manoeuvre in its **combined** ability to demonstrate both the illusion of climbing when the aircraft is pitched nose up, and the inability to accurately detect airspeed changes without reference to flight instruments?"						

Figure 3 demonstrates that of the 244 participants that experienced this manoeuvre, approximately 99% rated it as at least adequate in demonstrating SD and that greater than 93% of the participants rated it above average. Of note there was no statistical difference between the Initial and Refresher participants in their overall rating of the manoeuvre.

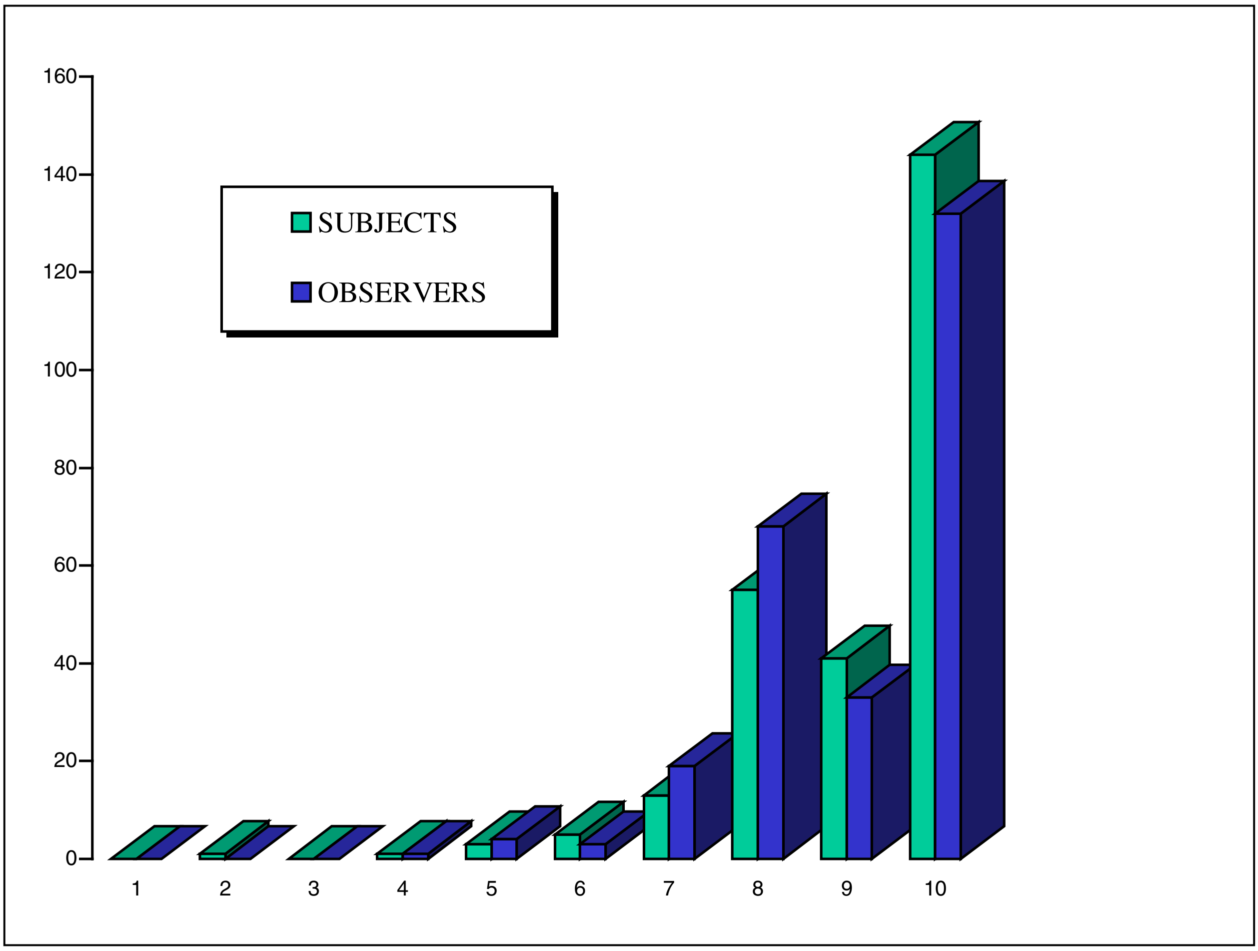
FIGURE 4: INADVERTENT DESCENT MANOEUVRE:



KEY: 1 = Extremely Poor 5 = Adequate 10 = Extremely Good COMBINED DATA			Break down of Initial **(I)** vs. Refresher **(R)** Participants			
STATISTICS	SUBJECTS	OBSERVERS	I SUB	I OBS	R SUB	R OBS
N=	105	152	62	105	43	47
Mean =	8.81	9.0	8.8	8.64	8.63	9.0
STDEV =	1.7	1.26	1.37	1.33	1.37	1.25
Median =	10	10	9	9	9	8
Mode =	10	10	10	10	10	10
Range	10-2	10-5	10-2	10-4	10-5	10-5
Question: "How successful would you rate the inadvertent descent manoeuvre in its ability to convince you that it is difficult to accurately sense the position, motion, and attitude of the aircraft when close to the ground in conditions of poor visibility?"						

Figure 4 demonstrates that of the 262 participants that experienced this manoeuvre, approximately 99% rated it as at least adequate in demonstrating SD and that greater than 95% of the participants rated it above average. Of note there was no statistical difference between the Initial and Refresher participants in their overall rating of the manoeuvre.

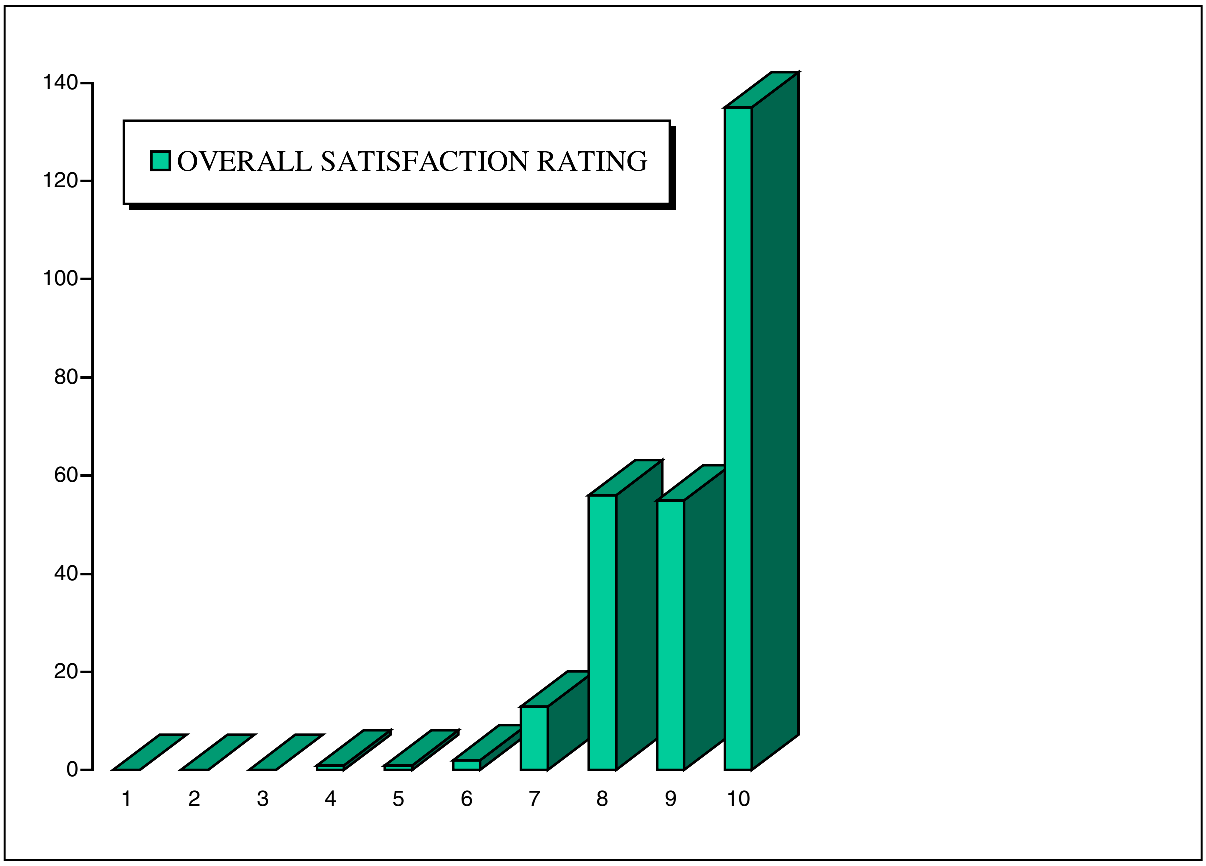
FIGURE 5: HOVER MANOEUVRES:



KEY: 1 = Extremely Poor 5 = Adequate 10 = Extremely Good			Break down of Initial **(I)** vs. Refresher **(R)** Participants			
COMBINED DATA						
STATISTICS	SUBJECTS	OBSERVERS	I SUB	I OBS	R SUB	R OBS
N=	263	260	168	166	95	94
Mean =	9.1	9.0	8.95	8.91	9.0	8.8
STDEV =	1.26	1.23	1.4	1.2	1.4	1.25
Median =	10	10	10	9	9	9
Mode =	10	10	10	10	10	10
Range	10-2	10-4	10-4	10-4	10-2	10-5
Question: "How successful would you rate the hover demonstrations in their ability to convince you that it is difficult to accurately sense the position, motion, and attitude of the aircraft when close to the ground in conditions of poor visibility?"						

Figure 5 demonstrates that of the 523 participants that experienced this manoeuvre (almost 100% experienced the manoeuvre as both a Subject and an Observer), greater than 99% rated it as above average in demonstrating SD. Of note there was no statistical difference between the Initial and Refresher participants in their overall rating of the manoeuvre.

FIGURE 6: THE OVERALL CUSTOMER SATISFACTION WITH THE SORTIE:



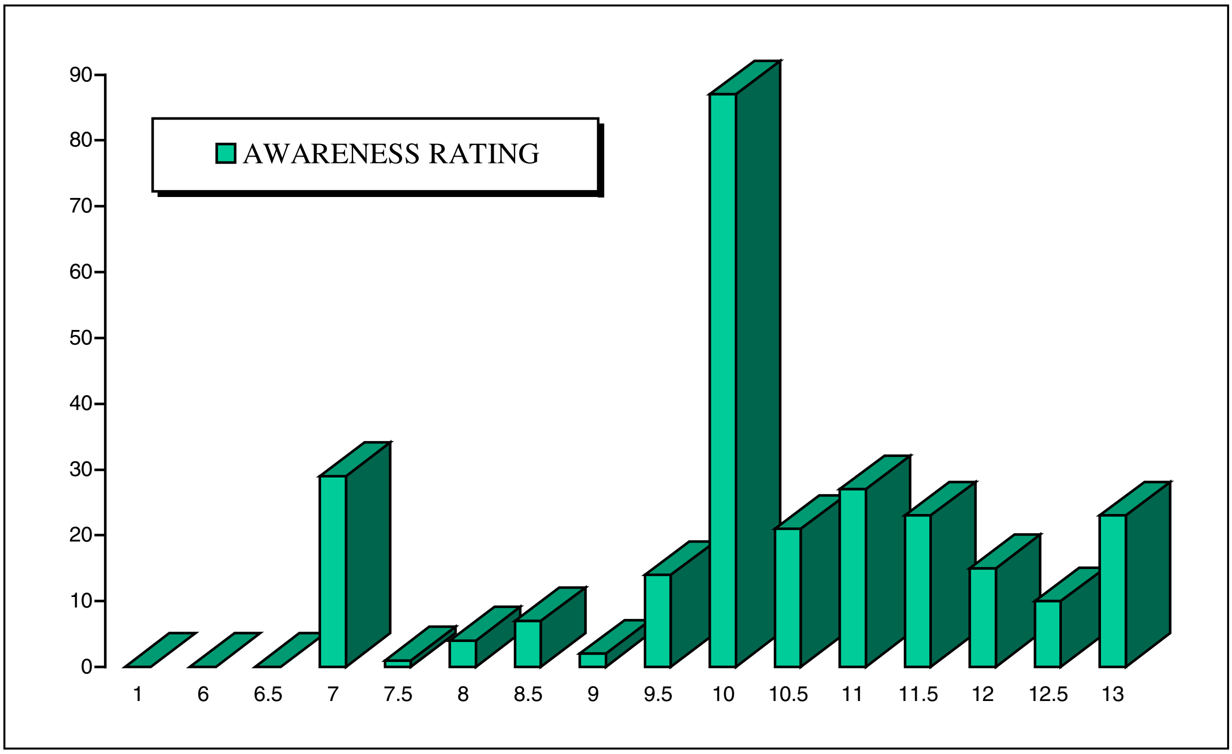
KEY 10 – Extremely Satisfied 5 - Adequately Satisfied 1 - Not Satisfied	INITIAL TRAINING	REFRESHER
Participants N = 265	167	98
Mean = 9.14	9.1	9.0
STDEV = 1.06	0.94	1.22
Median = 10	9	9
Mode = 10	10	10
Range = 10-4	10-5	10-4
Question: “Overall, how well did this demonstration sortie show the limitations of the orientation senses in flight?”		

Figure 6 demonstrates that of the 265 participants that experienced this SD Sortie, greater than 99% rated it as above average in demonstrating SD. Of note there was no statistical difference between the Initial and Refresher participants in their overall rating of the manoeuvre.

Post Sortie SD Awareness.

Participants were asked to rate their awareness of the limitations of the orientation senses in flight compared to their previous knowledge. The distribution of responses to this question is shown in figure 7. It should be noted that 100% of the respondents considered that the sortie felt that they were at least as aware post sortie, but that approximately 90% felt that they were more aware post sortie.

FIGURE 7: SD AWARENESS POST SORTIE:



KEY 13 – "Totally Enlightened" 7 - "The Same as Before" 1 - "I Know Nothing About SD"	INITIAL	REFRESHER
Participants N = 265	167	98
Mean = 10.3	10.5	9.6
STDEV = 1.63	1.48	1.67
Median = 10	10	10
Mode = 10	10	10
Range = 13-7	13-7	13-7
Question: "Compared with your awareness of the limitations of the orientation senses in flight **before** the sortie, how would you rate your knowledge now?"		

Individual comments assessing the SD training sortie demonstration.

90 individuals (34%) made comments regarding the sortie. All comments were supportive. A list of the most common and notable comments is as follows.

- "The Sortie was good/great/excellent/worthwhile/highly useful, etc" – 47 individuals made this type of comment.
- "The Sortie was useful in reminding us to fly with our instruments not by the seat of our pants/senses" - 8 individuals made this comment.
- "As an Instructor I feel this is a crucial training program for not only the novice student but also the experienced QHI with thousands of hours in the air" - 3 participants made this comment.
- "SD cannot be fully understood without this demonstration" - 1 participant.
- "As a QHI, I am sure that this sortie can and does save pilots and airframes" - 1 participant.

DISCUSSION

This assessment set out to determine the internal validity via the SAT process of the Army SD demonstration sortie and whether it is an effective adjunct to training aircrew in SD. The cross-section of aviators included a number of very experienced instructor pilots whose comments were most valuable, as they are well positioned to influence the executive authorities on training issues. It may be inferred from individual comments recorded by the study participants that they regard SD as a significant hazard associated with Army helicopter operations. Response data indicated that the quality of SD training during initial and refresher training is greatly enhanced by the sortie. The manoeuvres performed in the SD demonstration sortie, and the sortie overall, were extremely effective at demonstrating the limitations of the orientation senses. Furthermore, the sortie was given a significantly high rating via individual comments in its effectiveness to train aviators in SD than other available methods (didactic training).

The SD sortie has been previously externally validated in that the SD accident rate for the 10 years before the demonstration was introduced (2.04 accidents per 100,000 flying hours {1971 – 1982}) was compared with a similar period following its introduction (0.57 accidents per 100,000 flying hours {1983-1993}) [2,7]. The statistical analysis inferred a period effect of a highly significant reduction in the SD accidents rates since the sortie has been introduced. There are confounding factors in this analysis. Some factors will have tended to reduce the orientation error accident rate, e.g., the introduction to service of aircraft with automatic flight control systems and stability augmentation in the late 1970s; the installation of additional aircraft flight instruments (e.g., radar altimeters) in the early 1980s; the phasing out of predominantly single pilot operations in the mid 1980s and subsequent introduction of 2 qualified pilot crews for most sorties in the late 1980s; and a reclassification of the accidents to exclude the lesser damaged airframe in 1991. A counterbalancing factor that has tended to increase the orientation error accident rate is the much greater use of night vision goggles since the mid 1980s.

Notwithstanding these arguments, it is reasonable to assert that the SD demonstration sortie has contributed to reducing the accident rate in which SD is involved. It should be noted that both the U.S. Army and the Canadian Air Force have both recently added this sortie to their initial flight-training syllabus and it is hoped that these nations will carry out similar analysis in the future.

The purpose of this study was, however, to provide a measure of internal validation using the SAT Process. The results presented suggest that the SD sortie satisfies those requirements. It is evident that the participants in the study responded that not only were the individual demonstrations and the sortie overall satisfactory to excellent, but approximately 90% also noted that they were more aware of SD secondary to this training.

In this era of budgetary restraints for military training, it should also be noted that any additional flight training bears a cost both in terms of money and time spent training. In the Army, the Gazelle is used to fly the sortie. Using 1996 real military operating costs, a charge of approximately £90 per student has been calculated. The total cost over nearly 18 years of this training has been approximately £200,000 or an average annual sum of just over £12,000. The overall figure is a very small fraction of the replacement cost of even the least expensive in-service Army helicopter. The time spent performing the demonstrations to a class can be minimized by doing rotor-turning crew changes. In the Army, class sizes are usually 12 students; so 4 sorties can be completed within approximately 2 hours [1]. It is stressed that this demonstration does not seek to train the aviator in how to deal with SD once it has occurred; that is the responsibility of the QHI.

Although, the assessment of internal validity via the SAT Process was concluded to be successful, as Army mission requirements change and as the Army modernizes its rotary-wing fleet (for example Apache AH1), the Aviation Medicine Specialist must be vigilant and closely monitor the SD accident and incident rate to determine if syllabus changes are required.

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From Safety Net to Augmented Cognition: Using Flexible Autonomy Levels for On-Line Cognitive Assistance and Automation

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Summary

Human factors research into spatial disorientation (SD) and loss of situation awareness (SA) in the fast jet military pilot has led to consideration of systems for monitoring pilot behaviour and psychophysiology and for detection of performance degradation and incapacitation. These could be the basis of real-time countermeasures, such as a "Safety Net" system, assisting or taking over automatic control until the pilot is able to resume full control of the system. This paper looks at technologies developed under the UK MOD "Cognitive Cockpit" project for providing *cognitive assistance* through adaptive automation and decision support. The paper considers the requirements for monitoring and countermeasures for cancelling SD. It is argued that all three basic types of SD can be cancelled by effective real-time adaptive countermeasures using flexible levels of autonomy governed by pilot agreed plans. Through analysis and cognitive walk-through of a mission story-board, we show how the safety net concept can be extended by cognitive automation to provide augmentation of SA and decision making. Cognitive augmentation can be seen to mitigate the most dangerous form of insidious disorientation, by keeping the pilot in the control loop before SD sets in.

1. INTRODUCTION

Since the late 1980's, researchers in aviation human factors and medicine have been concerned about the effects of high mental workload and physiological stresses on the operators of fast-jet fighter aircraft, particularly the consequences of G-induced loss of consciousness (G-LOC), spatial disorientation (SD) and loss of situation awareness (SA). This led to consideration of the development of systems for detection of performance degradation and pilot incapacitation, and the potentially controversial concept of a "Safety Net" system, temporarily overriding the authority of the partially or fully incapacitated pilot until he/she is able to resume full control of the system. Generally, operators expressed guarded acceptance of the safety net concept, with concerns about system reliability and tactical utility of operator monitoring, advisory and recovery systems in an operational mission context. The need to override the authority of the pilot proved hard to sell.

Subsequently, many of the sub-components of the safety net system concept for providing significant risk mitigation have been successfully developed and implemented in operational systems. These include:

1) systems for automatic G-protection in aircrew life-support equipment,
2) improved sensor and computing technologies providing information fusion, situation assessment, mission management and decision support,
3) advanced control/display technologies for improved communication interfaces, and
4) new automation techniques for aircraft control and limitation of operation and performance, such as manoeuvre envelope protection, and aircraft/ground proximity warning and collision avoidance systems.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

However, full implementation of the safety net concept is yet to be achieved. In particular, there remains a need to develop sufficiently reliable, trustworthy systems for the monitoring and detection of operator performance degradation (e.g. G-LOC, SD, loss of SA), that can trigger credible, effective and tactically useful interventions, preferably without the need to override the pilot's authority.

Under the UK Ministry of Defence (MOD) Applied Research Program, a three-year program of human sciences led work on intelligent pilot aiding has been recently completed at DERA Centre for Human Sciences, Farnborough. This MOD "Cognitive Cockpit" (COGPIT) project successfully demonstrated the feasibility of providing automated *cognitive assistance* to aid the fast-jet pilot through coupling adaptive automation and decision support concepts with technologies for monitoring operator behaviour and psychophysiology (1). This application of *cognitive automation* focussed on aiding in a high cognitive load scenario, with possible distraction and reduced SA, involving the use of defensive aids and mission replanning in response to a pop-up threat. A key project goal was to enhance system adaptiveness in response to dynamically changing, time pressured mission environments. Achieving this needed development of detailed understanding of the operator requirements for control and management of automated and semi-automated tasks. It was found to be essential to provide a system for task management that retains the operator's authority and executive control of critical system functions, whilst enabling delegation of responsibility to the computer for the performance of tasks as required. This would require an appropriate balance of feed-forward and feedback information on task performance. The key to this problem was two-fold:

1) The provision of systems for monitoring and reasoning with contexts (pilot state, mission, and environment) with a high degree of context sensitivity i.e. both precision and accuracy.
2) The development of a simple, readily understandable and easily controllable set of flexible *levels of autonomy* and cognitive assistance, short of full automation, with an intuitive *cognitive interface* enabling effective *cognitive interaction*.

These requirements are believed to be central to the provision of a credible, trustworthy safety net system, which can successfully intervene under G-LOC, SD or loss of SA.

The purpose of this paper is to summarise the work and lessons learnt relevant to the safety net concept, with particular reference to the use of flexible levels of autonomy and the reliability of advanced techniques for operator functional state assessment. The aim is to describe the relevance of the system concepts for cognitive augmentation mitigating against loss of SA and the onset of SD.

2. SITUATION AWARENESS AND SPATIAL DISORIENTAION

2.1 Definitions and types

SA has been defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (2). Applied to the military aviation environment, SA would include elements such as navigation, tactics, communications, weather, aircraft capability, and spatial orientation (3). It is possible for a pilot to lose situational awareness. In one study, the majority of SA errors occurred as the result of failure to perceive the situation; that is, failure to detect information or misperception of information (4). It follows that failure to perceive one's spatial orientation can result in SD, defined as an incorrect sense of the position, motion or attitude of the aircraft or of the pilot within the fixed co-ordinate system provided by the surface of the earth and the gravitational vertical (5).

The mechanism of SD is complex, involving the interaction of the vestibular and somatosensory senses in conjunction with the visual axis. Recognition of SD and subsequent recovery requires the cognition of the pilot. Traditionally SD has been categorised as Type I, when the pilot is unaware that he is disoriented; Type II, he is aware that he is disoriented; and Type III, he is aware but is unable to overcome the disorientation. Type I SD is insidiously dangerous, whereas Type II and III SD are obviously dangerous. Clearly the most dangerous condition is that of Type I SD.

In a study of USAF mishaps from 1991-2000, spatial disorientation accounted for 20.2 % of all Class A mishaps, costing over $1.4 billion and 60 fatalities. The four most common contributors to SD mishaps in decreasing order of frequency were attention management, judgement/decision making, mission demands, and psychological factors (6). Because most of the contributors involve cognitive tasks, it should be apparent that an aircraft system that augments the cognitive ability of the pilot would decrease or eliminate the consequences of SD.

2.2 Real-time countermeasures

Initial applications of cognitive automation have focussed on aiding in a mission scenario with high cognitive load, distraction and high potential for reduced SA. A high level of SA and spatial orientation is required in military aviation in order to prosecute the mission, especially in single seat fast jets. With the increased technological ability of multiple role fighters and the capability of deploying anywhere in the world, any enhancement of a pilot's SA could provide the difference between success and failure. Today's pilots must cope with multifunction displays, multiple sensor sources, various audio inputs, avionic helmets, and real time information flowing in and out of the cockpit. Simultaneously the pilot must keep a running mental model of the mission and electronic order of battle.

In a way, this is no less true for the pilot of Unmanned Aerial Vehicles (UAV); in fact, enhancement of SA may be even more crucial since the UAV pilot is remote from the vehicle and, to some degree, out of the loop. Providing real-time feedback of the state of the UAV, the mission, and the cognitive load on the pilot is crucial to mission success. Manned or unmanned, the pilot cannot become spatially disoriented, losing the relationship of the aircraft to the earth. The consequence can be controlled (or even uncontrolled) flight into terrain. And in fighter pilot lingo, "a kill is a kill."

Cognitive automation has the capability to cancel the consequences of SD. Constantly monitoring the pilot's functional state, the aircraft and its environment, and the execution of the mission plan provides the platform for maintaining the highest degree of SA. The pilot cannot be caught in Type I SD, which essentially obviates the likelihood of controlled flight into terrain (CFIT). Even if the pilot does experience Type II SD, such as the leans, he either flies the aircraft with reference to instruments, or allows the aircraft to fly itself, based on the level of automaticity. In Type III SD, the cognitive automation should recognise that the pilot is not functioning, and the computer will take control until the pilot has recovered. If the cognitive automation prevents SD, USAF data show that $1.4 billion could be saved and 60 fatalities prevented.

3. COGNITIVE AUTOMATION

3.1 Cognitive Automation Tasks

Cognitive automation provides an intelligent assistant to the fast jet pilot. This assistant has two main goals: it must prevent the pilot from being overloaded, by doing things that he would otherwise be doing; and it must help the pilot by providing him with the information he needs, when he needs it. These goals break down into eight tasks (1):

- MONITORING PILOT: watching the pilot to see what he is doing and how he is coping with flying the mission
- MONITORING ENVIRONMENT: watching the outside world, the aircraft systems and incoming information to identify anything that the pilot needs to know or do something about
- MONITORING MISSION PLAN: keeping track of what the pilot is doing and what he needs to do in the near future
- REPLANNING MISSION: working out what should be done by the pilot in response to unexpected situations
- UPDATING MISSION PLAN: keeping the mission plan consistent and up to date
- CONFIGURING COCKPIT: making sure that the pilot has the information he needs in the form he needs it, and that the controls he is using are configured to let him do the things he wants to do quickly and easily
- DECIDING AUTOMATION: working out what tasks should be automated rather than left to the pilot
- AUTOMATING TASKS: actually carrying out various tasks for the pilot

A simplified model of the overall process within the designed system is shown in the activity diagram in Figure 1. Cognitive automation monitors three aspects of the situation:

- the environment, which includes the outside world and the state of the aircraft systems;
- the mission plan, to indicate which tasks the pilot is currently engaged in and what he will be doing shortly;
- and the pilot, to take into account his cognitive state.

These feed forward information into the replanning of the mission, the automation of tasks that have previously been identified as requiring automation and configuring the cockpit to supply the pilot with information relevant to the task he is doing. The results of monitoring the pilot, replanning the mission, automating tasks and deciding automation cause updates to the mission plan.

The performance of these activities is a continual process throughout the mission. The various aspects of the situation are continually monitored, and may result in changes in the use of displays and other output devices, in the actions recommended, and in the automation level adopted.

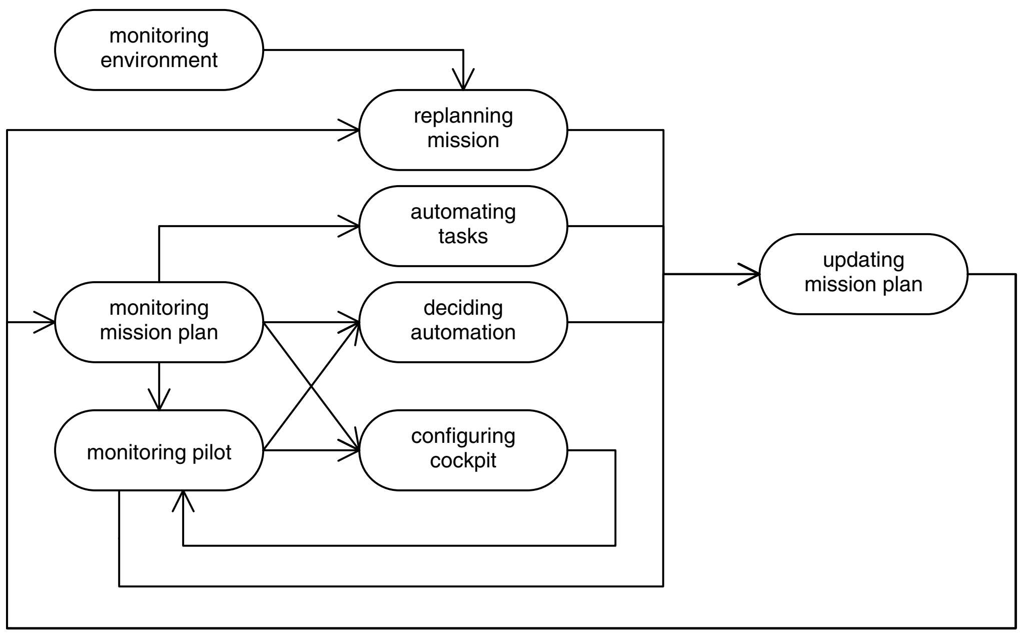

Figure 1. Cognitive automation tasks and information flows

3.2 Cognitive Automation Systems

Three classes of cognitive automation sub-systems or modules are needed to perform the goals and tasks identified above.

Situation Assessment Support System (SASS) – This is a module that monitors the status of the aircraft situation and the outside environment and recommends actions. This module is concerned with on-line mission analysis, aiding and support provided by real-time, multi-agent Knowledge Based Systems (KBS) software. This system is privy to the current mission, aircraft (e.g. heading, altitude and threat) and environmental status, and is also invested with extensive *a priori* tactical, operational and situational knowledge. Overall, this system provides information about the objective state of the aircraft within a mission context, and uses extensive KBS to aid and support pilot decisions (7). Knowledge acquisition (KA) under the COGPIT programme has focussed on the following areas:

- plan assessment - checking how the mission is progressing,
- system health - checking how the aircraft systems are performing,
- attack phase - carrying out the attack on the target,
- and Defensive Aids System (DAS) and re-routing - identifying when DAS and re-routing should be employed to counter threats and weather.

Knowledge-level models of these tasks have been built, and decision support has been implemented and successfully demonstrated for DAS re-routing in a high cognitive load scenario, with the potential for loss of SA. The SASS decision support provided the basis for augmented cognition and maintained SA. Further KA from subject matter experts is needed to build the knowledge base for implementing the correct decision support in tactical scenarios involving reduced pilot capacity and pilot incapacitation (loss of SA, SD, G-LOC). In an SD scenario, SASS would receive pertinent aircraft and environmental information (e.g. rapid accelerations, high G manoeuvres; unusual aircraft attitudes, positions, flight path trajectories; unusual rates of climb/descent, loss of altitude and energy; closure on obstacles, terrain). SASS would provide recommendations on appropriate timings and actions plans for tactically correct aircraft and mission control (e.g. automated flight control, re-routing, threat countermeasures, and terrain collision avoidance).

Cognition Monitor (COGMON) – This is a module that monitors the pilot's physiology and behaviour to provide an estimation of pilot state. This module is concerned with on-line analysis of the psychological, physiological and behavioural state of the pilot. Primary system functions include continuous monitoring of workload, and inferences about current attentional focus, ongoing cognition and intentions. It also seeks to detect dangerously high and low levels of arousal. Overall, this system provides information about the objective and subjective state of the pilot within a mission context. This information is used in order to optimise pilot performance and safety, and provides a basis for the implementation of pilot aiding (8). In an SD scenario, COGMON would receive relevant pilot information, estimate the cognitive affective state (e.g. detecting and identifying G-LOC onset, attentional focussing, overload, fatigue, drowsiness), and provide information on the pilot's ability to perform tasks (e.g. alerting, full automation).

Tasking Interface Manager (TIM) – This is a module that monitors the mission plan and manages the interface with which the pilot is presented. This module is concerned with on-line analysis of higher-order outputs from COGMON and SASS, and other aircraft systems. A central function for this system is maximisation of the goodness of fit between aircraft status, 'pilot-state' and tactical assessments provided by the SASS. These integrative functions enable this system to influence the prioritisation of tasks and, at a logical level, to determine the means by which pilot information is communicated. Overall, this system allows pilots to manage their interaction with the cockpit automation, by context-sensitive control over the allocation of tasks to the automated systems (9). The TIM functional architecture comprised modules for goal-plan tracking and for interface, timeline, automation and task management utilising a blackboard for goal-plan tracking information. In a SD scenario, TIM would receive SASS and COGMON information, identify conflicts and discrepancies, and integrate these with information on the mission plan tasks and goals. TIM would manage the implications for the performance of tasks (e.g. non-adherence to plan, non-responsiveness to planned changes), assist or automate re-planning and task performance as required, and provide the pilot with appropriate feed-forward and feedback control information.

4. MONITORING THE PILOT'S FUNCTIONAL STATE

The COGMON sub-system has a specific role within the cognitive automation system aimed at identifying the cognitive affective state of pilots, and may be seen as a means of identifying how well the pilot is coping with current task demands. This can be used to identify means of adaptively automating tasks within the cockpit environment. The COGMON uses four classes of information to estimate the cognitive affective state (Figure 2). These are physiological measures, behavioural measures, subjective measures and contextual measures. It is the key interactions between each of these classes of measures that allow predictions to be made of the type of cognitive operation being performed. When this is combined with a subjective assessment of the workload experienced by individuals when performing that specific task, and the physiological correlates of high workload, for example, then estimates of an individuals ability to cope with current task demands may be made.

Advanced flight systems also give access to the wealth of information regarding the local environment in which the pilot is operating. For example, orientation of aircraft, threat status, G experienced by pilot, altitude etc. This provides a context in which our physiological, behavioural and subjective measures can be interpreted. This information has to be more than merely of academic interest if the problems presented by spatial disorientation are to be mediated. The output from the COGMON are designed to provide a useful index of the pilots status, and should enable principles of adaptive automation to be employed for the safe re-orientation of the pilot and aircraft.

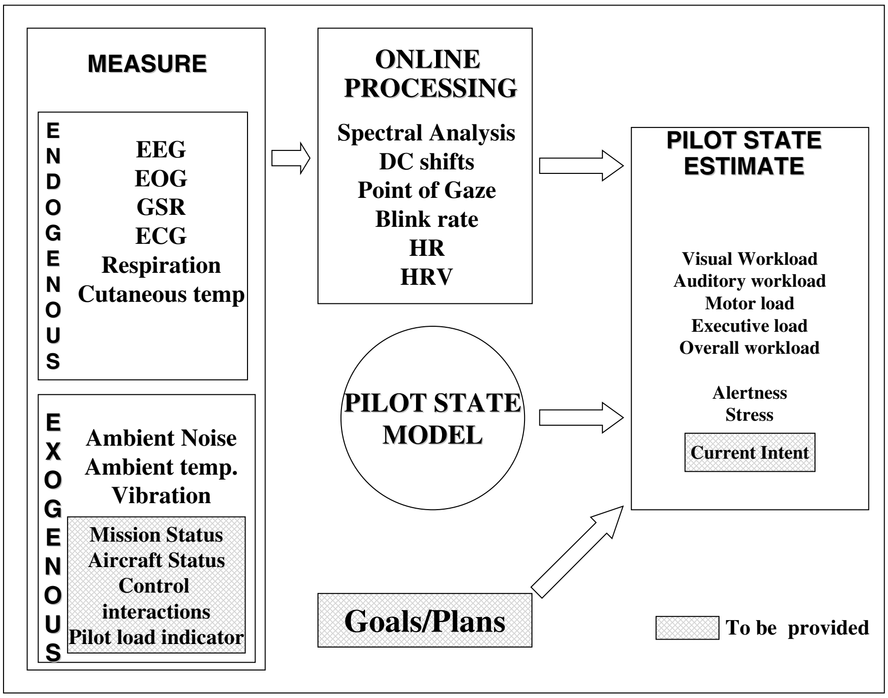

Figure 2. Structure of COGMON measures and state estimates

The spatial disorientation literature presents a picture in which conflicting visual, vestibular and proprioceptive information leads to increased disorientation. This is exacerbated by the requirement for the 'high level' forms of cognitive processing, such as those associated with strategic decision making, and attention management. Indeed it has been reported that combining unambiguous sensory information leads to reduced levels of perceived workload during the maintenance of situational and spatial awareness. The mechanism of operation of the COGMON is metaphorically illustrated below.

The situation whereby the attitude of the aircraft is nose-down, and accelerating, results in a shear force being present on the otolith organs of the inner ear. This combined with the relational movement of the direction of gravity, combines to present a perceived horizontal flight path. This illusion can be easily disambiguated if the pilot is 'head out' and can refer to the out of the window (OTW) reference frame. However if operational factors require the pilot to be head down, performing complex tasks, such as interacting with a digital map display, or calculating re-routing options, then the OTW frame of reference cannot be accessed. There is a growing body of evidence which suggest that increased levels of workload are a contributing factor to accidents involving SD. Furthermore if the task requires a high degree of attentional tunnelling, the ability to process external stimuli and 'task share' will be further diminished. Thus monitoring aircraft systems will enable the nose-down attitude and the increase in air-speed to be identified. The interaction of the pilot with the map display could indicate that focus of attention is head-down, and that attention is being invested in visuo-spatial information processing. This will also serve to limit the ability of the pilot to react to additional visuo-spatial information, and may serve to compound the disorientation instigated by the illusion of horizontal flight. Furthermore the analysis of EEG recorded over posterior and parietal scalp, those areas which overlie the areas of the brain in which visuo-spatial information is processed, shows high levels of coherence between activity recorded at parietal and occipital scalp sites. This type of activity may indicate high levels of visuo-spatial workload. This example demonstrates that available information may be integrated to develop a picture of the cognitive affective state of the pilot in which their ability to respond to external stimuli is diminished due to current task demands.

5. AUTOMATION AND CONTROL OF TASKS

5.1 Tasking Interfaces

The idea of a tasking interface exploited the lessons learnt from the US Army's RPA program (10). It arose from the need to be able to predict pilot expectations and intentions with reference to embedded knowledge of mission plans and goals. The aim was to provide an adaptive or "tasking" interface that allowed the operators/pilots to pose a task for automation in the same way that they would task another skilled crewmember. It afforded pilots the ability to retain executive control of tasks whilst delegating their execution to the automation. A tasking interface necessitated the development of a cockpit interface that allowed the pilot to change the level of automation in accordance with mission situation, pilot requirements and/or pilot capabilities. It was necessary that both the pilot and the system operated from a shared task model, affording communication of tasking instructions in the form of desired goals, tasks, partial plans or constraints that were in accord with the task structures defined in the shared task model.

Allowing pilots to choose various levels of interaction for the tasks they are required to conduct can mitigate the problem of unpredictability of automation. The TIM can utilise the monitoring and analysis of the mission tasks provided by the SASS combined with the pilot state monitoring of the COGMON to afford adaptive automation, adaptive information presentation and task and timeline management.

5.2 Contractual Autonomy

Providing flexible levels of autonomy for the performance of tasks and functions is a key requirement for implementation of the tasking interface concept. An important development under the COGPIT project was the framework devised for providing only the necessary and sufficient levels of autonomy with TIM support. The resultant framework is known as the system for pilot authorisation and control of tasks, or PACT, described in Table 1(11, 12).

Primary Modes	Levels	Operational Relationship	Computer Autonomy	Pilot Authority	Adaptation	Information on performance
AUTOMATIC		**Automatic**	Full	Interrupt	Computer monitored by pilot	On/off Failure warnings Performance only if required.
ASSISTED	**4**	**Direct Support**	Advised action unless revoked	Revoking action	Computer backed up by pilot	Feedback on action. Alerts and warnings on failure of action.
	3	**In Support**	Advice, and if authorised, action	Acceptance of advice and authorising action	Pilot backed up by the computer	Feed-forward advice and feedback on action. Alerts and warnings on failure of authorised action.
	2	**Advisory**	Advice	Acceptance of advice	Pilot assisted by computer	Feed-forward advice
	1	**At Call**	Advice only if requested.	Full	Pilot, assisted by computer only when requested.	Feed-forward advice, only on request
COMMANDED		**Under Command**	None	Full	Pilot	None performance is transparent.

Table 1. Bonner-Taylor PACT framework for pilot authorisation and control of tasks

PACT is based on the idea of *contractual autonomy*. Borrowing an aircrew term from co-operative air defence, the idea is that the pilot forms a *contract,* or set of contracts, with the automation using the PACT system by allocating tasks to PACT modes and levels of automation aiding. The contract defines the nature of the operational relationship between the pilot and the computer aiding during co-operative performance of functions and tasks. Autonomy is limited by a set of contracts, or binding agreements, made between the pilot and the computer automation system governing and bounding the performance of tasks. Through PACT contracts, the pilot retains authority and executive control, while delegating responsibility for the performance of tasks to the computer.

5.3 Control of PACT

PACT succeeds in reducing the number of automation or autonomy modes required to three - namely, fully automatic, assisted or pilot commanded - with a further four secondary levels nested within the semi-automatic, assisted mode, which can be changed adaptively or by pilot command. The PACT system uses military terminology for categories of support for Army land forces military operations (At call, advisory, in support, direct support) to afford usability and compatibility with military user cognitive schemata and models. It provides realistic operational relationships for a logical, practical set of levels of automation, reduced to six levels of autonomy, with progressive operator/pilot authority and computer autonomy supporting situation assessment, decision making and action (Figure 3). Mission functions and tasks, at different levels of abstraction allocated individually or grouped in related scripts or plays, can be set to these levels in a number of ways:

- Pre-set operator preferred defaults,
- Operator selection during pre-flight planning,
- Changed by the operator during in-flight re-planning, probably using Hands on Throttle and Stick (HOTAS), touch screen, and Direct Voice Input (DVI) commands (11).
- Automatically changed according to operator agreed, context-sensitive adaptive rules.

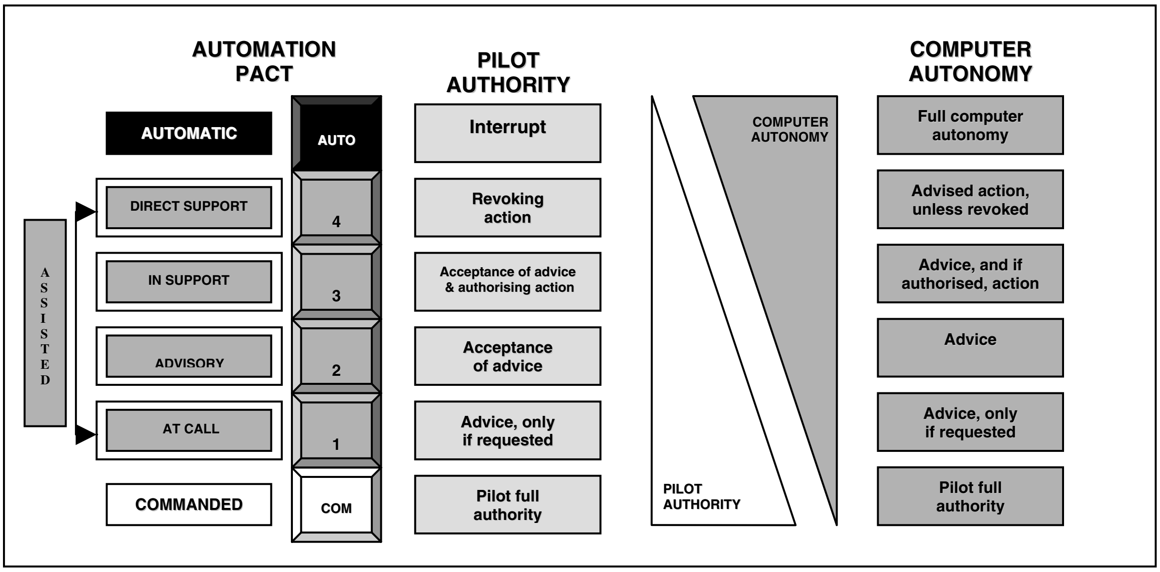

Figure 3. PACT levels of pilot authority and contractual autonomy

5.4 Intervention Strategy

An overview of the proposed adaptive intervention strategy is illustrated in Figure 4. In SD scenarios, pilot awareness is variable and unpredictable. Thus, it is important that the PACT level changes can be triggered adaptively in response to contextual input from COGMON, SASS and TIM mission goal-plan tracking (GPT), carried out in accordance with the pilot's pre-set PACT contracts. COGMON, SASS and TIM will contribute different triggering information, depending on the type of SD involved. SASS will be important for Type I SD with only weak COGMON inferences (e.g. distraction, inattention). There should be strong SASS, COGMON and TIM indications for Type II and III SD. Table 2 summarises the kinds of indications and inferences that could be available from monitoring the pilot, the environment and the mission plan in Type I, II and III SD scenarios.

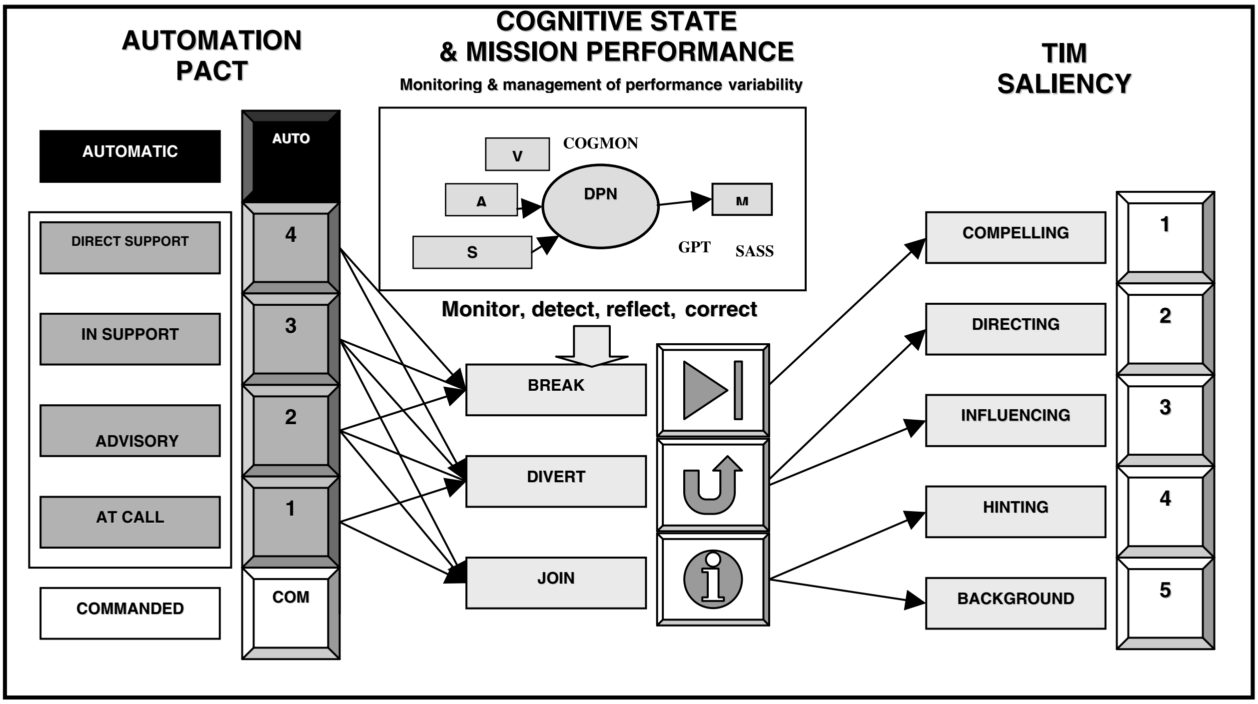

Figure 4. PACT adaptive intervention

The intervention strategy seeks to monitor and manage the variability in performance through a barrier system approach (monitor, detect, correct, reflect), and through appropriate cognitive stream interventions (join, break, divert). TIM feedback and feed-forward control messages are provided to the pilot with appropriate multi-modal intervention saliency (background, hinting, influencing, directing, compelling) developed to manage attentional and cognitive bias (13). The ability to manage the saliency TIM messages should be particularly useful for communicating adaptive countermeasure information in SD scenarios with complex sensory and cognitive demands. Different intervention saliency requirements will apply when the pilot is distracted and unaware of the problem (Type I SD), compared with when aware of conflicting sensory inputs and needing to focus (Type II SD), or when unable to overcome compelling SD (Type III SD). Figure 5 illustrates how the prototype cockpit display formats were developed to communicate TIM feed-forward and feedback control information with managed saliency in the Head Mounted Display (HMD) and Head Down Display (HDD). Auditory voice messages, with directional sound, provided powerful augmentation of the visual information.

As discussed earlier, tasks can be pre-allocated to *possible* PACT level contracts by the pilot before the flight in mission planning. The individual task PACT levels (defaults and contingencies) should be set to mitigate the risks to achievement of the individual task goals. The TIM Task Manager distinguishes between *pending, active* and *completed* tasks for the current mission element. Individual tasks progress from pending, to active and to complete as the mission progresses. An example of the Task Manager status is highlighted in the TIM control station display developed for the COGPIT demonstration (Figure 6). The panels shown in Fig 6 are clockwise, from top right, as follows:

- Inferencing Display (list of goals and tasks, indicating currently active)
- COGMON display - load estimates (green = low; yellow = medium; red = high) of pilot states (visual, verbal, auditory, spatial, left hand, right hand, motor, alertness, tactile)
- TIM Task Display - pending, active and completed tasks, with associated active or default and contingency PACT contracts, indicating the current and permitted alternative PACT levels.
- COGMAN Display - visualisation of visual, verbal, auditory, left hand, right hand loads, and location of gaze

TASK DESCRIPTION	SD SCENARIO		
	TYPE I Unaware Not responding	**TYPE II Aware Trying to cope**	**TYPE III Aware-Unable to overcome**
MONITORING PILOT: watching the pilot to see what he is doing and how he is coping with flying the mission	*Weak COGMON indications* Behavioural: Head-down, focussed not OTW referenced. Normal, unresponsive actions e.g. map gaze location, no compensatory flight control activity, normal speech comms. Psychophysiological: Normal relaxed EEG, ECG,GSR, DC shifts, low HR, HR variability, blink. No clear inference re in or out of the loop control, or of intervention need.	*Strong COGMON indications* Behavioural: Reactive e.g. visual focussing on instruments, compensatory flight control inputs, reduced speech. Psycho-physiological: Raised alertness, high load, raised stress, focussed attention e.g. alert EEG, ECG, GSR, raised HR, HR variability, reduced blink duration, frequency. Pilot in the loop, but assistance may be appreciated.	*Clear COGMON indications* Behavioural: Scrambled or emergency procedures, speech communication Psycho-physiological – High stress, cognitive overload, sensory conflict EEG, ECG, GSR, HR, HRV, blink, gaze, nystagmus G-LOC: inaction, no speech and psycho-physiological correlates Evidence of pilot out of the loop. Assistance almost certainly required.
MONITORING ENVIRONMENT: watching the outside world, the aircraft systems and incoming information to identify anything that the pilot needs to know or do something about	*Strong SASS indications* Unexpected changes, drifts, trends in aircraft attitude, altitude, position, speed, acceleration, velocity vector, flight path. Orientation towards terrain, obstacles, threats. Early external indications of possible need for cautionary warning, awareness.	*Clear SASS indications* Significant departures, unusual aircraft attitude, altitude, position, speed, acceleration, velocity vector, flight path. Approaching terrain, obstacles, threats. Delayed or incomplete countermeasures. N.B. Does not always apply. Type II can be associated with normal flight parameters. Assistance almost certainly required.	*Clear SASS indications* Extreme, unsafe aircraft attitude, altitude, position, speed, acceleration, velocity vector, flight path. Immediate terrain, obstacles, threats. None or ineffective countermeasure actions. Immediate action required.
MONITORING MISSION PLAN: keeping track of what the pilot is doing and what he needs to do in the near future	*Weak TIM inferences* Current task still as planned. No clear indication that the pilot intends to take a different flight trajectory, or to change the mission plan, or that the changes are inadvertent and unintended. No clear inference of intervention need from plan/task tracking alone. Discrepancies between environment and pilot information can indicate potential awareness problem and warning need.	*Strong TIM inferences* Recognised task change. Current task not as planned, nor pending. Identifiable as priority flight control recovery action. Increased risk to mission plan. Needs assistance with recovery task and possibly in assessing the consequences for the mission plan.	*Clear TIM inferences* Current priority flight control recovery task not being performed effectively. Pilot safety and mission goals at extreme risk. Needs immediate automatic recovery of flight control and probably assistance with re-planning the mission, particularly if incapacitated.

Table 2 Monitoring SD

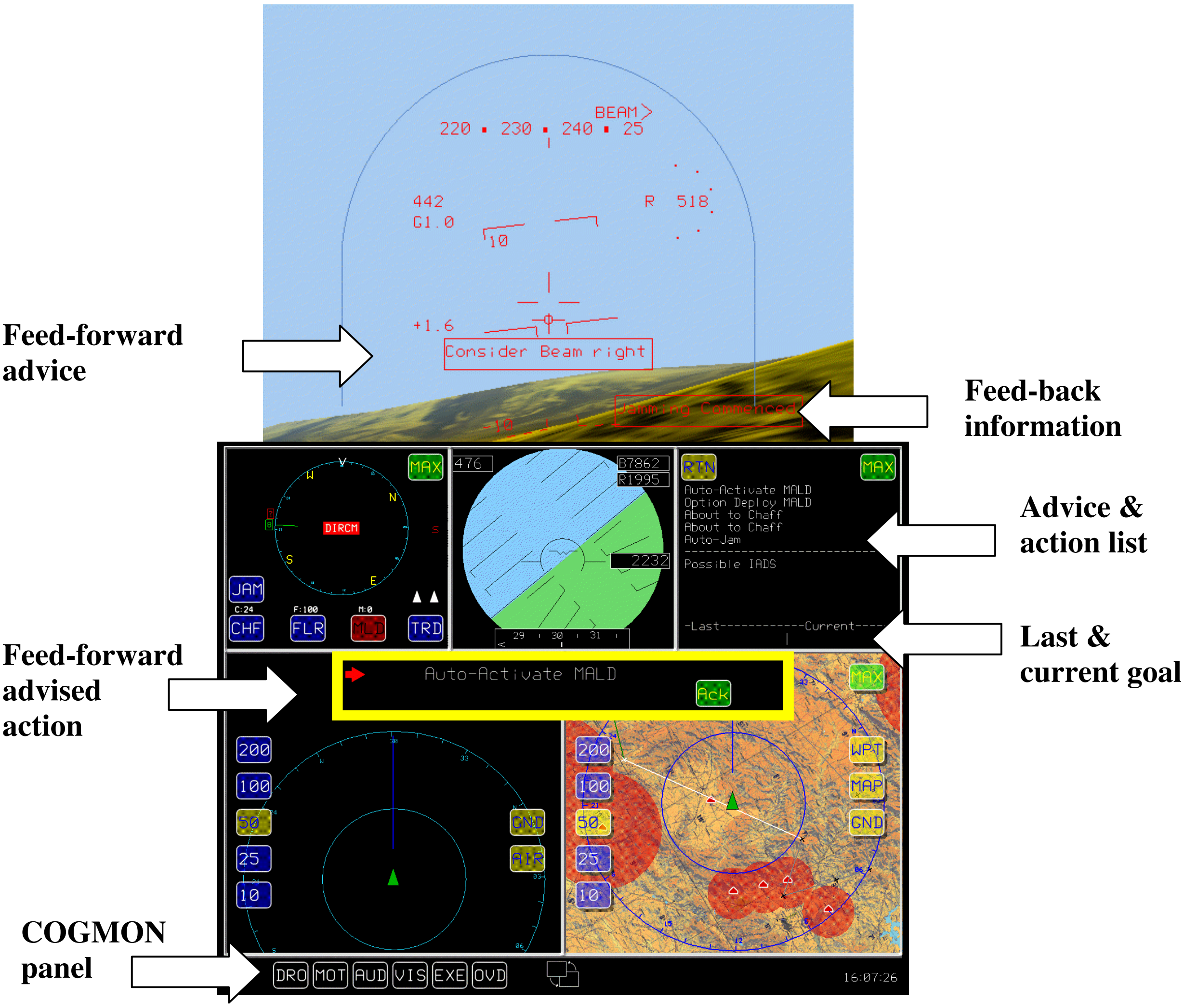

Figure 5. Prototype cockpit HDD and HMD with TIM control information.

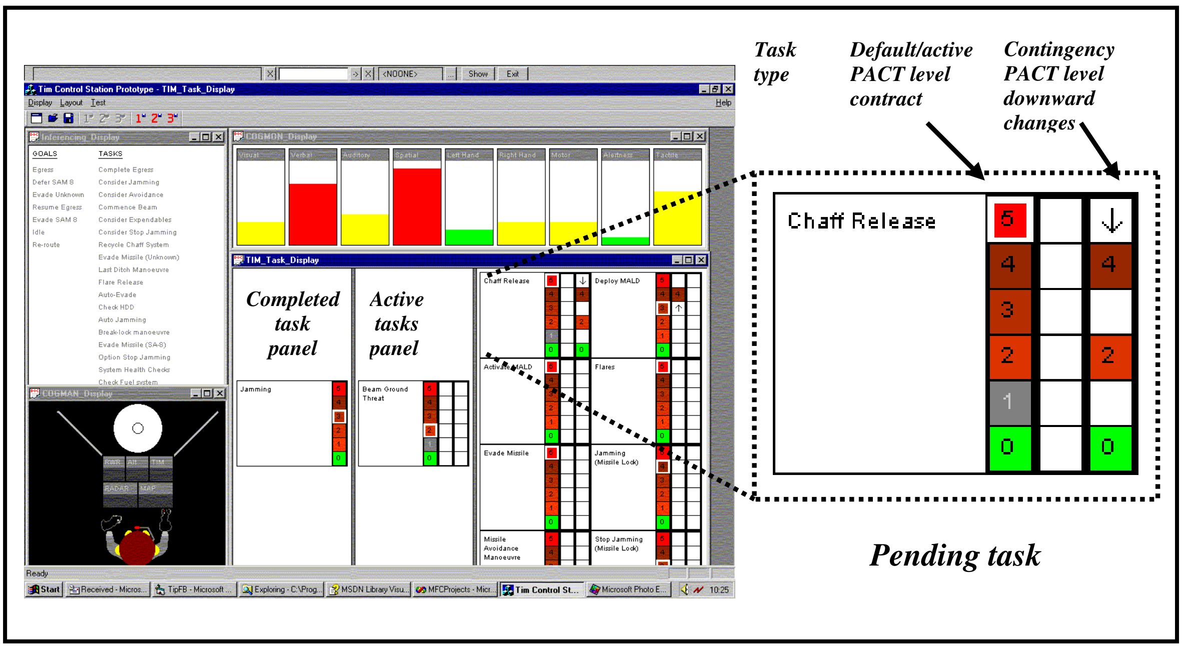

Figure 6 TIM Control station display of tasks and PACT levels

In Figure 6, the left-most panel of the TIM Task Display shows the most recently completed task ("Jamming"), whereas the active ("Beam ground threat") and pending panels ("Chaff release"; "Activate MALD" etc) show multiple tasks as necessary. Individual tasks are represented as boxes containing their name together with their associated *possible* default and contingency PACT level contracts, which range from 0 (Commanded) to 5 (Automatic). The "Chaff Release" task is highlighted with its default PACT level display set for 5 (Automatic). Two additional PACT level displays are available to the right of this default display to show contingencies for how the PACT level can change by increasing (↑) or reducing (↓) PACT levels according to pre-set contracts. In this example, when the default PACT level is set at 5, it is possible under certain circumstances (e.g. Chaff remaining < 30%) for the PACT level to change down to 4, 2 or 0 (but not 3 or 1). Explanatory information on the circumstances for triggering changes (contract details) is stored and available for inspection. PACT levels that are unavailable are also indicated (reverse contrast caption) as shown for pending Chaff Release task, default PACT level 1.

6. COGNITIVE AUTOMATION SD COUNTERMEASURES

In SD scenarios, pilot awareness and capacity for countermeasure action is variable and unpredictable. Table 2 has shown the indications and inferences that could be available from monitoring the pilot, the environment and the mission plan in Type I, II and III SD scenarios. In the proposed cognitive automation control system (Figure 1), these monitoring functions feed forward information into mission re-planning, the automation of tasks, and configuring the cockpit with relevant task information. In SD scenarios, these control tasks can be considered as the constituents of real-time cognitive automation SD countermeasures. Strong environment (SASS), pilot state (COGMON) and mission plan (TIM) indications are likely to be available for detecting Type II and III SD, and for guiding the kinds of countermeasures envisioned under the safety net concept. This includes the possibility of temporarily automating control of safety critical system functions, with implicit or explicit pilot consent, in the case of the partially or fully incapacitated pilot until he/she is able to resume full control of the system. For Type 1 SD, the availability of strong and sensitive environment monitoring information for comparison with pilot state and mission plan information, raises the possibility of countermeasures for this insidious and particularly dangerous form of SD, and is believed to be most significant. Type 1 and II SD countermeasures seem likely to take the form of augmenting SA, decision support and cognitive assistance i.e. designed to keep the pilot in the control loop. It seems that in considering Type 1 or II SD, where possible cognitive augmentation and assistance that keeps the pilot in the control loop, is probably always preferable to substituting, if only temporarily, fully automatic control systems for the pilot. This could be for a number of good reasons associated with risks of automation control, including loosing the tactical benefits of pilot in the loop SA, the inherent unpredictability of automation, automation mode awareness, delayed pilot recovery of control, automation bias, overuse and trust, and pilot skill fade.

Table 3 summarises the implications for Type I, II and III SD countermeasures of the cognitive automation tasks of re-planning the mission, updating the mission plan, configuring the cockpit, deciding automation, and automating tasks. It seems clear that there are significantly different implications for re-planning, cockpit configuration task management and automation, cognitive augmentation with the SD types.

- *Re-planning and Updating the Mission Plan.* Type I SD indications are unlikely to warrant immediate re-planning and task changes, but might usefully trigger cautionary warnings and advice to confirm the mission plan and task. However, TYPE II and Type III SD indications are likely to warrant checking the mission plan and flight control task. Type III SD indications may require automatic re-planning including automation of mission and flight control tasks.
- *Configuring the Cockpit.* Type I SD indications probably warrant the need for alerting cautionary and warning HMD, HDD and audio information augmenting SA, with intelligently managed saliency, and advice to check and confirm understanding of the mission and flight control status. Type II SD indications probably warrant salient feed-forward orientation and recovery information using most effective HMD, HDD, audio and tactile display cueing methods, and offer of automatic recovery options. Type III SD indications probably require provision of most salient feed-forward HMD, HDD and voice information and intuitive controls (HOTAS, DVI) for automation recovery options, and availability of pilot state feedback.

TASK DESCRIPTION	SD SCENARIO		
	TYPE I **Unaware** **Not responding**	**TYPE II** **Aware** **Trying to Cope**	**TYPE III** **Aware** **Unable to overcome**
REPLANNING MISSION: working out what should be done by the pilot in response to unexpected situations	No clear indication of immediate re-planning need. Early external indications from SASS of need for cautionary warning, and possible need to confirm the mission plan.	Inferred immediate priority task and goal change (safe recovery) with possible need to automatically check, and advise any implications for the mission plan.	Automatically assess any implications of pilot (e.g. incapacity) and aircraft state (e.g. position) for the mission plan and ability of pilot to perform tasks. Re-plan to include automation of tasks as appropriate.
UPDATING MISSION PLAN: keeping the mission plan consistent and up to date	No immediate update required.	Update mission plan if required.	Update mission plan as required.
CONFIGURING COCKPIT: making sure that the pilot has the information he needs in the form he needs it, and that the controls he is using are configured to let him do the things he wants to do quickly and easily. • Head Down Display (HDD) • Helmet Mounted Display (HMD) • Direct Voice Input (DVI) • Hands on throttle and stick (HOTAS)	Provide pilot alert/warning information. Indicate need to check information on aircraft flight control and mission plan and confirm understanding of status. Manage level of TIM f-fwd message saliency. For awareness: TIM4 Hinting or TIM3 Influencing. For immediate awareness: TIM2 Directing, or TIM1 Compelling. HMD & HDD and voice e.g. “Check attitude” or “Pull-up, pull-up”.	Support f-fwd orientation and recovery action with high saliency cueing: TIM2 Directing; TIM1 Compelling Aiding options include: 1) status HMD (e.g. NDFR), HDD (e.g. BAI), 3-D audio, tactor. 2) Priority recovery action (e.g. “Pull-up, pull-up”; HMD sky pointers; directional tactors). 3) Tactically safe manoeuvre (e.g. voice “Better terrain right”). 4) Flight path director predictor (pathway in the sky). 5) Force-stick tactile cueing, +override. 6) Automatic recovery option (e.g. “Option auto pilot”).	Provide information and controls for automation recovery option. Provide high saliency f-fwd information: TIM 1 Compelling. HMD,HDD & voice: “Auto avoid” “Brace, brace”. Provide HOTAS manual and DVI auto selection and over-ride options. Provide pilot state indicator control panel (self report). Provide COGMON state estimation feedback information HMD, HDD and voice (TIM3 Influencing) e.g. “Reduced pilot capacity”.
DECIDING AUTOMATION: working out what tasks should be automated rather than left to the pilot. • Flight Control System (FCS) • Ground Collision Avoidance System (GCAS) • Mission Control System (MCS) • Defensive Aids System (DAS) – Jamming, Manoeuvre Chaff, MALD	No immediate full auto requirement. Pre-set PACT Assisted mode level changes triggered by events (SASS): 1) FCS: PACT1 At Call to PACT2 Advisory 2) GCAS: PACT2 Advisory to PACT3 In Support 3) DAS: PACT3 In Support	Pilot selected, or pre-set PACT Assisted mode level changes triggered by events (COGMON, SASS, TIM): 1) FCS Recovery: PACT2 Advisory to PACT3 In Support 2) GCAS: PACT3 In Support to PACT4 Direct Support 3) MCS: Re-planning PACT1 At Call to PACT2 Advisory 4) DAS: PACT3 In Support to PACT4 Direct Support	Pre-set PACT Assisted mode level changes triggered by events (COGMON, SASS, TIM): 1) FCS Recovery: PACT3 In Support to PACT4 Direct Support 2) GCAS: PACT4 Direct Support 3) MCS: Replanning PACT2 Advisory to PACT4 Direct Support 4) DAS: PACT4 Direct Support
AUTOMATING TASKS actually carrying out various tasks for the pilot	*Alerting & advice.* FCS PACT2 Advisory GCAS PACT3 In Support	*Advice and action, if required.* FCS PACT3 In Support GCAS PACT4 Direct Support MCS PACT2 Advisory	*Advised action, unless revoked.* FCS PACT4 Direct Support GCAS PACT4 Direct Support MCS PACT4 Direct Support DAS: PACT 4 Direct Support

Table 3 SD Countermeasures

- *Deciding Automation and Automating Tasks.* Type I SD indications probably warrant adaptive Assisted PACT level changes to provide automatic Flight Control System (FCS) alerting and advice (PACT 2 Advisory), and raised Ground Collision Avoidance System (GCAS) support for action (PACT 3 In Support). Type II SD indications probably warrant further raising of adaptive Assisted PACT levels to provide support for both advice and action (e.g. FCS : PACT 3 In Support; GCAS: PACT4 Direct Support; DAS: PACT 4 Direct Support) and raised Mission Control System (MCS) Re-planning (PACT 2 Advisory). Type III SD indications probably warrant raising automation level of all mission and safety critical systems, including FCS recovery and MCS, to provide action, unless revoked (PACT 4 Direct Support).

7. STORYBOARD COGNITIVE WALKTHROUGH

In order to illustrate the operation of the proposed prototype cognitive automation system, a mission storyboard, route map and time-line is reported as an annex to this paper. This is a modification to the DAS Re-route storyboard used by DERA CHS for the successful MoD Final Customer Demonstration, ARP26f2.3 Automated Decision Support assignment, held at Farnborough on 23 March 2001. The scenario, events and activities are believed to be illustrative of a difficult mission with high levels of workload and stress. The level of mission difficulty is designed to defeat a pilot without adaptive aiding, cognitive automation and decision support. The story-board events and action timeline, partially illustrated in Figures 8, 9 and 10, were flown successfully and repeatedly executed by Sqn Ldr Phil O'Dell RAF, Fast-jet Project Test Pilot, DERA Boscombe Down. The storyboard builds a typical insidious Type I SD event in the context of a deep interdiction attack mission. This shows the operation of the PACT system for DAS and Re-routing automation as developed and demonstrated by DERA CHS. In summary, after executing a successful target attack in a threat environment, during the subsequent egress mission segment, the pilot encounters 2 pop-up SAM threats, which are countered using the automated DAS actions. Fusing of the 2nd SA8 close aboard leads to a fuel leak, pressurisation failure and fuel falling below chicken requiring urgent computer-assisted re-routing to safe airspace and recovery to a diversion airfield. This is followed by COGMON and TIM inferring reduced pilot capacity further triggering of changes to DAS automation levels. In the final segment illustrated in Figure 11, a Type I SD event is added to the closing reduced pilot capacity scenario. COGMON indications of stress, and TIM tracking of pilot tasks and actions. This describes adaptive cognitive automation of SD countermeasures operating in accordance with the capabilities and constraints discussed above, and identified in Tables 2 and 3. Appropriate monitoring and countermeasures for Type II SD and Type II SD are illustrated in Figures 12 and 13.

8. CONCLUSIONS

SD can be detected from monitoring environmental, behavioural and psycho-physiological indicators. It should be possible, in the near future, to implement systems that use this information together with embedded task models, to identify and to discriminate Type I, II, and II SD states. We have described how using this monitoring information, SD can be cancelled by effective real-time adaptive countermeasures, in ways that are trustworthy and that follow provably correct pilot agreed plans. An important step has been the development and successful proof-of-concept demonstration of an intuitive, easily controllable set of flexible levels of autonomy for cognitive assistance and automation. This enables the cognitive interaction needed for maintaining pilot authority and delegating responsibility to automation for the performance of tasks. Through the use of flexible levels of autonomy, the safety net concept can be extended to provide cognitive augmentation that mitigates against loss of SA before SD sets in, keeping the pilot in the control loop.

9. ACKNOWLEDGEMENTS

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ANNEX

DAS/RE-ROUTE SD STORYBOARD

The scenario is for a 2015-2020 singleton FireFox aircraft, carrier borne option, on deep interdiction, day low-level, weather dependent mission against a target airfield, with airborne refuel, SWEEP and SEAD, and with Fulchrum, SA8 and SA 14 mission threats. The pilot is Sqn Ldr Mark "Dell" Cafferky-Seares. The intelligent aiding system (TIM + SASS & COGMON) is nick-named "ODIN" after the Norse God of wisdom. The story-board segment begins in the egress phase of the mission, some 5 minutes after the successful airfield attack, as indicated on the route plan (Figure 7).

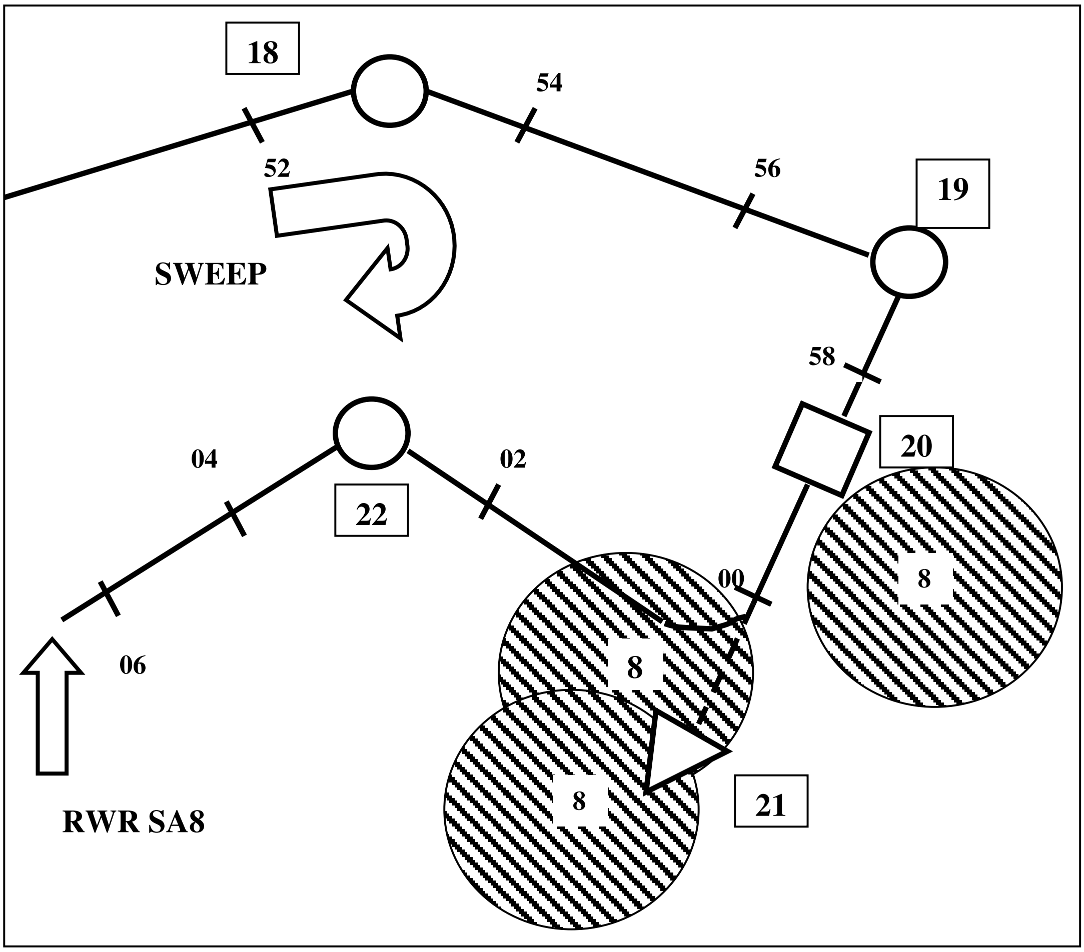

Figure 7 Route Plan for Attack and Egress

Timeline: 16:06:30 – 16:08:00 (map minutes)
Profile: Egress route flown at 100–300 AGL at 450kt.
Sensors in use: Radar (TF in a GPWS role and air-to-air), RWR, FLIR, MAW
Local Weather: 5/8th cloud at 5000ft. Visibility 10 km. Some stratus on hills above 8000ft. Surface wind 320/15.
Pilotage: Manual
Route position: Wpt 22 to 23

Pre-SD Segment

16:06:30 RWR indicates **SAM contact.** ODIN advises Dell possible Integrated Air Defence System, followed by automated DAS action (PACT3 jamming, PACT2 cued beam manoeuvre, PACT5>4 chaff, PACT3 MALD release, PACT5 stop jamming). The time-line in Figure 8 illustrates the external events and cockpit messages in this segment up to the PACT 4 deployment of chaff.

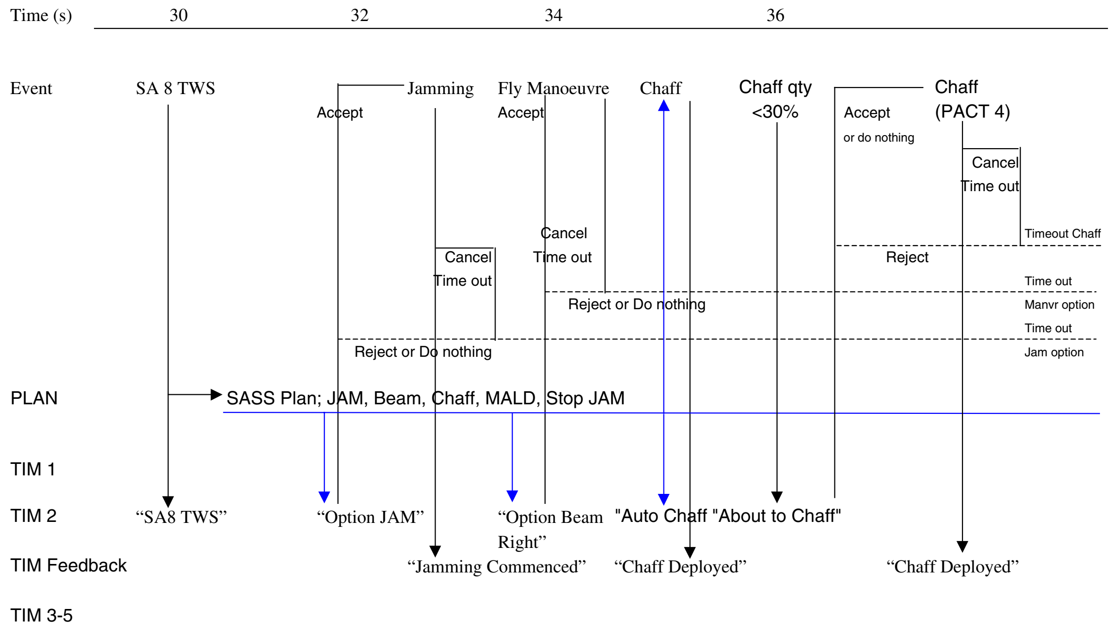

Figure 8. Time-line SA8 TWS to PACT 4 Chaff Deployed.

16:06:39 ODIN advises **Chaff failure** and Dell manual recycle of chaff system power. MAW indicates **missile inbound**, followed by ODIN automated PACT5 flares. With chaff still inoperative, ODIN (advised by COGMON) detects DELL's **inattention to missile** (gaze head-down focussed on chaff re-activation), and provides repeated **audio alert** "Missile left, unknown" (TIM1) and HDD/HMD cueing leading to Dell DVI "Acknowledged". ODIN PACT5 **auto-evade** is interrupted by Dell's manual **last ditch manoeuvre** at impact minus 5. ODIN DVO provides MAW count down "Missile impact in 6,5,4,3,2,1" followed by DIRCM activity **fusing missile** at 200 metres.

16:06:46 RWR indicates **SAM radar lock** followed by ODIN **DAS action** (PACT4 jamming, PACT2 cued 140 break lock manoeuvre). RWR indicates **SAM launch**, then MAW ODIN DVO counts down "Missile impact in 6,5,4,3,2,1" followed by Dell last ditch manoeuvre and DIRCM activity **fusing missile close** aboard, causing airframe **buffeting**.

16:07:10 SAM fire control radar ceases. ODIN PACT5 system check detects and advises **fuel leak**, followed by **pressurisation failure**, restricting ceiling to 20,000 feet, followed by **cross-feed failure**, restricting fuel **below chicken**.

The fuel loss triggers re-route calculations by ODIN (advised by SASS), which factors the fuel level of below chicken into **urgent re-route**. ODIN provides advice to Dell in HMD and HDD **"**Calculating re-route". Dell acknowledges this information, through DVI "Acknowledged".

SD SEGMENT

16:07:30 Key Decision Point: ***Method of recovery to safe airspace***

Task: *Recover aircraft to diversion field*

ODIN provides advice to Dell in HMD and HDD to clear aircraft "Consider jettison drop tanks".

Task: *Release drop-tanks*

There is no immediate response from Dell to this ODIN advice.

Re-route level for egress is set in the mission plan at PACT 2 (Advice only). ODIN (advised by SASS) provides the information to allow presentation of proposed routes on the digital map and advises two routes to Dell recommending route A as preference. Dell requests more information on the two routes by DVI " More info route A" then "Head down 3 more info route B".

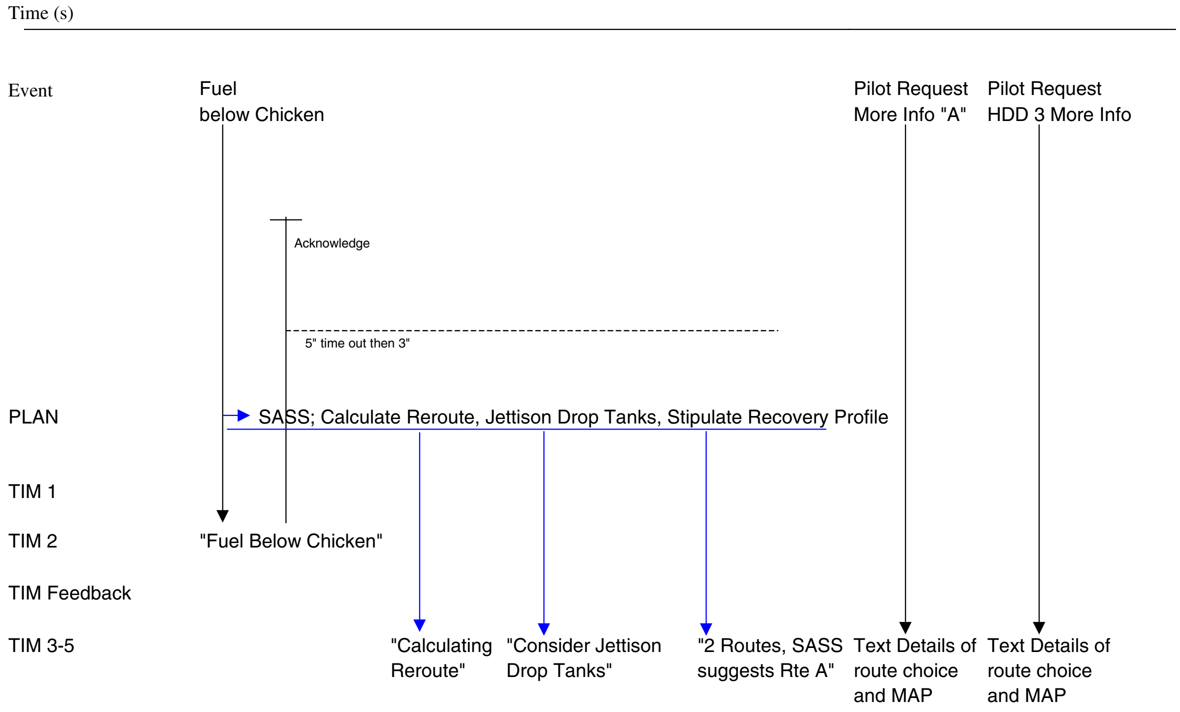

Figure 9. Time-line Chicken Fuel to Re-route assessment.

ODIN provides information on each route in the HDD in sequence Route A followed by Route B, allowing Dell to toggle between maps.

Dell accepts advice for high level transit direct to diversion. Dell requests specific details on re-route A using DVI "Head down 3 details route A"

ODIN provides the detail on re-route A to Dell in HDD "Route A Climb to 20 000 ft Heading 200 deg Prepare TRD".

Task: *Gain altitude and traverse directly to diversion field;*
Task: *Prepare TRD;*
Task: *Monitor fuel supply*

Dell requests using DVI "More information pressurisation". ODIN responds HDD "Max ceiling 20000 feet due to pressurisation failure".

ODIN (advised by COGMON) interprets that Dell is suffering some degree of stress, which affects Dell's state and reduces his capability. ODIN (via COGMON) detects that Dell's gaze remains head-down on the re-route information, with sustained focussed attention, and estimates high visuo-spatial load.

ODIN's previous call "Consider release drop tanks" has produced no acknowledgement and no action response from Dell. Thus, the *release drop tanks* task remains pending.

There is no advised altitude or heading change, or Towed Radar Decoy (TRD) preparation action in response to the re-routing advice. These tasks also remain pending (advised by TIM). At this time, ODIN (advised by SASS) notes a loss of altitude.

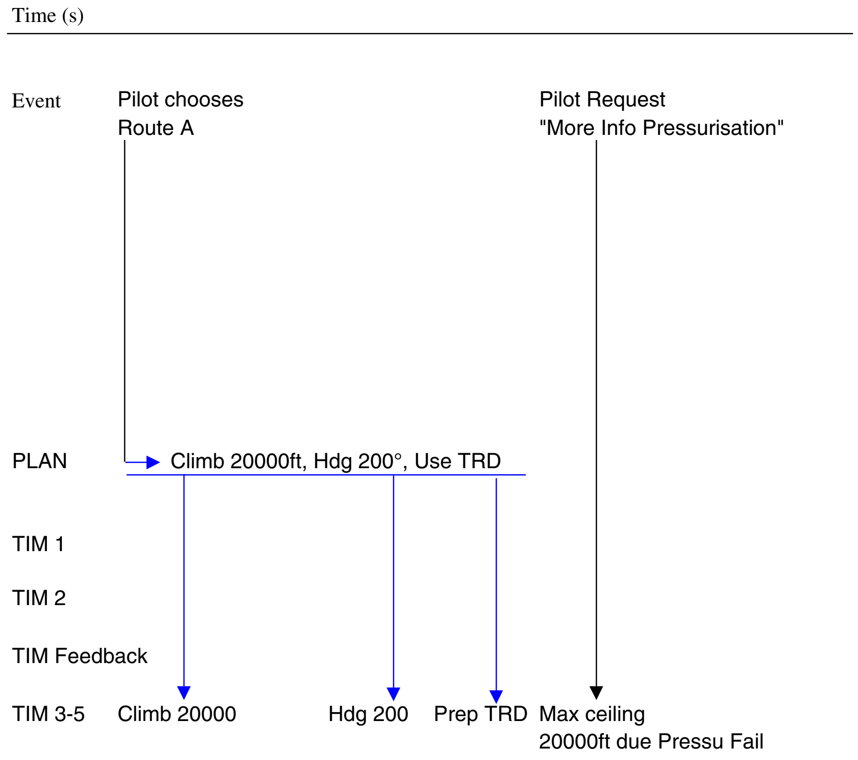

Figure 10. Time-line Re-route advice to Pressurisation query.

ODIN uses this information combined with the re-route information provided by SASS to change the level of automation, as agreed by the pilot in mission planning, and to provide SD countermeasures. The Flight Control System is changed from PACT 1 (At Call) to PACT 2(Advisory), and the pilot is notified. ODIN advises Dell by DVO "Check altitude". Dell hears and accepts the advice by DVI "Acknowledged". The Ground Collision Avoidance System is changed from PACT 2 (Advisory) to PACT 3 (In Support). ODIN advises Dell by DVO "Check flight plan". Dell accepts the advice by DVI "Accept". ODIN (via COGMON) monitors Dell visually checking the HDD SASS re-routing advice for Route A. Dell then initiates the climb to 20000ft, steers to heading 200, and initiates deployment of the TRD. ODIN (via TIM) infers the pilot's intent and current active tasks are: *Gain altitude and traverse directly to diversion field; Prepare TRD;*

As agreed by the pilot in mission planning, following an SD event, the levels of the remaining ECM countermeasures available to the aircraft are increased, as the re-route will cross a SA-6 MEZ.

The ECM automation level was set in the mission plan for egress at PACT 3 (Advice and action if authorised). ODIN assesses the pilot's capability and determines that it should be increased to PACT 4 (advice and action unless countermanded).

Flare automation is set in the mission plan for egress at PACT 3 (Advice and action if authorised). ODIN assesses the Dell's capability and determines that it should be increased to Level 4 (advice and action unless countermanded).

Missile avoidance manoeuvre automation level for egress is set in the mission plan at PACT 3 (Advice and action if authorised). Given the fuel restriction ODIN changes this automation level to PACT 2 (Advice only).

The DAS PACT information is automatically displayed on a HDD automation page. This is to allow Dell to query and/or over-ride any of the adaptive PACT changes. Dell requests information on these changes using DVI "*More information PACT change*" TIM provides advice in HMD and HDD display "Reduced pilot capacity - SD countermeasure". These monitoring and countermeasures for Type I SD are illustrated in Figure 11; possible procedures for Types II and III SD are illustrated in Figures 12 and 13.

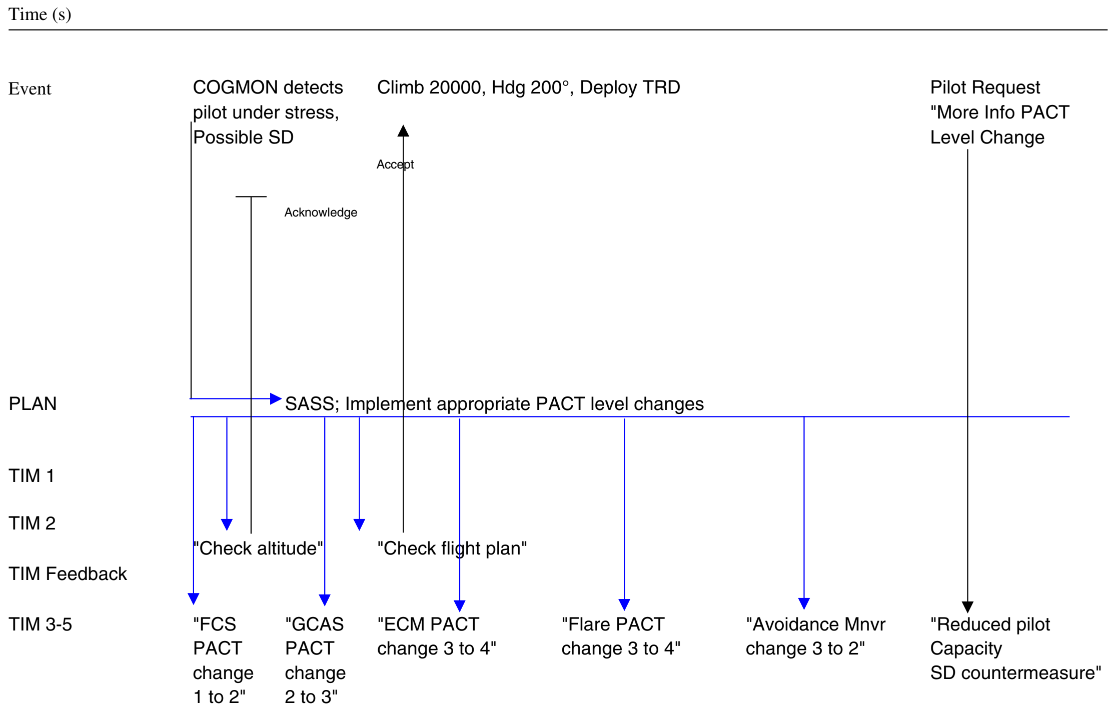

Figure 11. Timeline SD Type I Countermeasures.

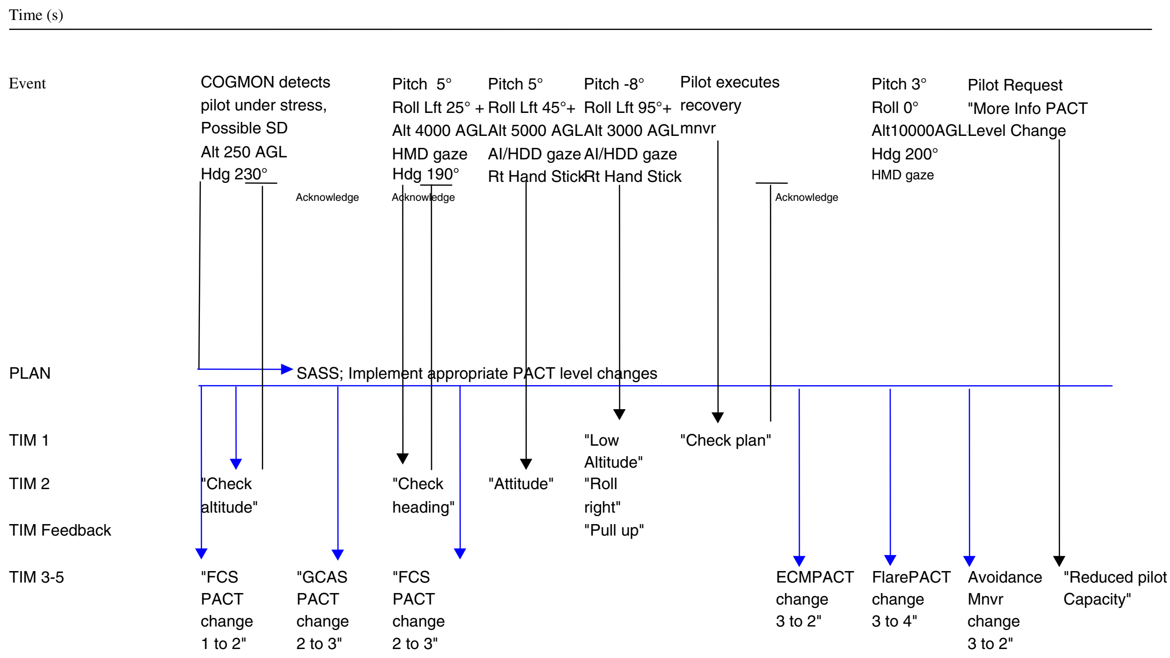

Figure 12. Timeline SD Type II Countermeasures.

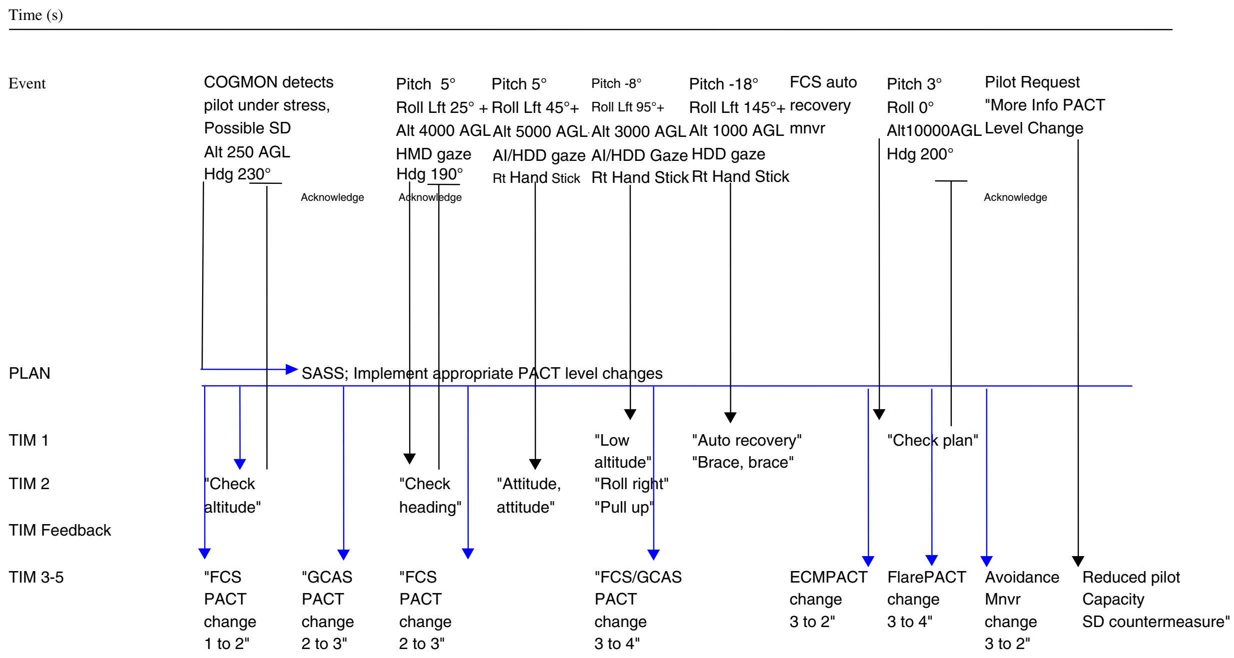

Figure 13. Timeline SD Type III Countermeasures.

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On the Possibility of Counteracting or Reducing G-Induced Spatial Disorientation With Visual Displays

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Summary

The possibility of counteracting or reducing g-induced spatial disorientation in fighter aircraft with visual displays is discussed in connection with the "classical" distinction between focal/ambient vision and inside-out/outside-in attitude display concepts. A relatively simple and uncomplicated laboratory method is presented that is utilized for exploring primarily visual flow coupling with spatial orientation. In part building on some experimental results from using the method some schematic implementation examples are illustrated, and some preliminary display design guidelines are also suggested.

Frames of reference

The controversial debate about what frame of reference we should use for attitude displays is still not entirely settled. The issue concerns whether to use an inside-out or outside-in representation, and the debate is almost entirely about its presentation in the central visual field. A review article by Previc and Ercoline (1999; see also Johnson & Roscoe, 1972) presents the various arguments for the two positions and shows that empirical results, overall, are in support of an outside-in format as the best candidate for reducing SD accidents. However, are we really optimizing the support of the pilot's spatial orientation with the substitution of one central visual field presentation with another?

It has now and then been argued that one shortcoming with cockpit instrumentation is precisely that it focuses on foveal or central vision (e.g., Leibowitz, 1988; Malcolm, 1984; Wickens & Hollands, 2000). This makes instrument information transfer dependent on directed attention and unsuited for direct perception of spatial orientation. Of course, this is not to deny the importance of the traditional flight instruments that represent the position of the aircraft relative the ground in various ways, e.g., horizontal gyro, altimeter, or head-up display (HUD) symbology. These instruments, however, require the pilot to direct attention to them, and are therefore in competition with other attention demanding tasks. Not surprisingly, the risk for SD accidents increases dramatically during low visibility when spatial orientation can only be maintained from intentional inspection of flight instruments. (Unrecognized SD - type I - is here of special importance.) Thus, although showing a potential for reducing some SD mishaps and fatal accidents, an outside-in instrumentation does not seem to be sufficient for really solving the problems of spatial disorientation.

This seems to leave us with a choice between research strategies, a choice between focusing research on: (1) "attention-requiring central vision interface principles", and (2) the mechanism for perceiving spatial orientation in every-day life. The first alternative could mean that we adopt the outside-in format and are more or less satisfied with this intervention. The second alternative challenges us to improve display characteristics to make the recreation of critical perceptual factors of the real visual scene realistic, optimal, and more effectively functional. The direct perception of spatial orientation relies on the characteristics of the whole ambient visual field and it is typically not dependent on attention. The

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problem is therefore not just to provide efficient visual information about spatial orientation, but also to counteract possible influence on the normal mode of perceiving spatial orientation. For instance, the part of the cockpit available to the peripheral visual field provides information about no-change in spatial orientation.

This alternative specifically outlines the exploration of characteristics of a wide-angle display, or peripheral displays, with an inside-out format. Further, this strategy leaves the question open about what kind of format attitude presentation in the central visual field should have. A combination of inside-out/outside-in formats is therefore not unlikely. Thus, this could lead to somewhat of a new kind of "hybrid" attitude display or rather a combination of frames of reference: An outside-in representation in the central visual field (HDD, HMD or HUD) with an inside-out format presented in the visual periphery (HMD or HUD). If an outside-in format is implemented on existing HUDs it actually means a superimposition on the view of the real background world in conditions of good visibility of ground and horizon, and thus a natural version of this combination. In fact, this kind of presentation is conceivable in that "proponents of the outside-in format have argued that such a format is both flyable on the HUD and possibly even superior in this case as well" (Previc & Ercoline, 1999, p. 385).

The main point to be made, however, is that *we need a visual aid that better resonates with the mechanism normally underlying spatial orientation to significantly reduce or counteract SD.* That is, the pilot's perceptual processing needs to come in contact with the crucial factors of the natural situation of viewing ambient earth surroundings with horizon that cause spatial illusions to be overcome. *We need to reconstruct the dominance of vision in perceiving spatial orientation.*

Preliminary guidelines for an effective visual display interface

What visual factors then are contributing to the fact that there are relatively few aircraft accidents due to spatial disorientation when visibility is good? Again, the obvious factors are of course the stable ground/horizon with the motion generated optic flow (Gibson, 1979; Lee, 1980). The effectiveness of optic flow for maintaining spatial orientation has often been emphasized, and, among others, Flach and Warren (1995) have investigated utilization of its geometrical properties to support spatial orientation. Most probably due to technological shortcomings especially regarding implementation, however, these properties of the flow field have been presented predominantly in the central visual field (e.g., Flach, Warren, Garness, Kelly, & Stanard, 1997; see the WrightCAD display in Flach, 1999). By contrast, von Hofsten and Rosander (1997) insist on emphasizing the importance of stimulated visual periphery from presentation of similar optic flow information in a wide-angle display.

Can visual displays be constructed in such a way as to convey the crucial information that supports spatial orientation? Can we recreate the crucial information on visual displays to make it sufficiently effective in supporting the pilot's spatial orientation and thus reduce spatial disorientation mishaps? It may be unlikely that helmet mounted displays (HMDs) technically capable of presenting sophisticated wide-field views can be provided in cockpits in the near future. It is perhaps more plausible that we can implement some of the HUD principles to approach the benefit of real wide-field presentation. Then again, HMD technology is a developing field in focus by several interested parties.

Most critical is if and how "stability" is accomplished in order to get it firmly anchored as an external frame of reference, and thus induce "perceptual believability". This primarily involves the compensation of any movement of the pilot and aircraft with a sufficient temporal resolution, and together with good optic solutions, it will compellingly contribute to making it a background frame of reference. Spatial resolution or visual scene realism are not as critical if presented on peripheral displays on a HMD. For instance, consider Kappé (1997; and Kappé, Erp, & Korteling, 1999) in a successful attempt to improve visual perception in a virtual environment by adapting display characteristics to the properties of the visual system:

> "By means of a head-slaved display presented on three adjacent displays, a detailed image can be presented in the viewing direction, surrounded by a sparse peripheral image on the remaining area of the displays…Clearly, peripheral displays had a positive effect on driving performance and spatial orientation,

> even though they presented a relatively small amount of information. A peripheral display presents information to the ambient visual modality, which improves (ego) motion perception and spatial orientation. In the present study, both the head-slaved display and the peripheral display presented the same virtual environment, albeit at a different level of detail…The results of the present experiments show that display effectiveness can be improved by adapting display characteristics to the properties of the visual system. Changing the virtual viewing direction is an effective method of increasing the field of regard, but is only effective when the images are presented at their proper position in the optic array, for instance by use of a head-slaved or head-mounted display…A head-slaved display surrounded by a sparse peripheral image was found to be just as effective as a wide-field three-channel display."
>
> Kappé, 1997, pp. 36-37

This implies that we do not have to use a sophisticated, wide-angled full-view connected HMD, but instead can use *three separate fields-of-views ("display surfaces") with the two peripheral ones presenting an artificial horizon and optic flow with (quite) sparse detail (lower resolution).*

A methodological attempt: Trying to get there!

In order to generate guidelines for an optimal design of the visual interface some of the basic parameters for exploration have to do with how much of the visual field needs to be covered by the display. For instance:

1. How much information needs to be presented in the central visual field?
2. How much of the peripheral field needs to be employed?

In general, these issues could be investigated by using human centrifuge settings where the g-force varies while visual vertical is constant, i.e., Dynamic Flight Simulator with visual presentation of parts of a surrounding environment. These are more of ultimate test situations, however, and it is more practical to manipulate the visual vertical and keep the g-force constant, a situation easily accomplished in the laboratory by presenting a visual flow to subjects wherein the visual vertical varies. In this way, we are trying to obtain key indications of the effectiveness of various visual factors, and later evaluate those in the Dynamic Flight Simulator.

The rationale is that the importance of the visual determinants relative to the ones based on the g-force (proprioception and equilibrium sense) can be measured by its effect on balance. By varying the presentation of visual flow in combination with a moving horizon and study their effects on postural responses, we thus get indications of what properties of the visual display are effective in the perception of spatial orientation. Thus, our methodological approach so far is a relatively simple and uncomplicated laboratory method in which we evaluate how effectively different visual display factors affect the perceived equilibrium of the body. This is done by measuring the amount of sway induced when visually simulating different transformations of body orientation.

In the experimental situation the participant is positioned in an erect stance in front of three integrated computer monitors, with the monitors displaying simulated flight by motion of ground and horizon of a visual scene as viewed from a banking or rolling aircraft. The postural responses are measured by means of a head-tracker system that registers the 3-D changes of the participant's head position.

The computer monitors are connected and positioned so that the displays cover an integrated visual field of 150° horizontally and 34° vertically, including gaps between displays of 7.5° horizontally. See Figure 1. The basis for the visual stimuli is a flat virtual landscape with texture element gradient towards a clearly defined horizon beneath a starry sky, schematically shown in Figure 2. The fields of view of this virtual environment presented on the displays are determined by the position of the viewpoint as indicated in Figure 1, and they are constant throughout the presentations, i.e., the presentations are not head-slaved.

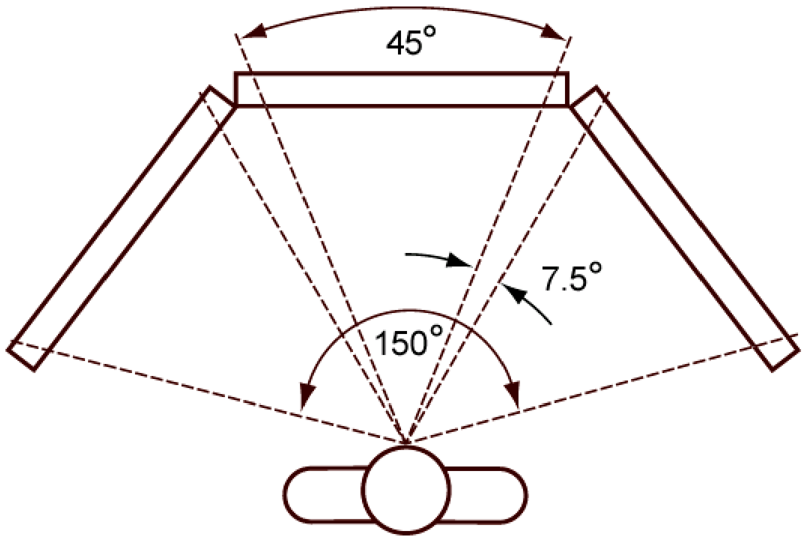

Figure 1. Top view of the visual fields covered by the display surfaces of the computer monitors.

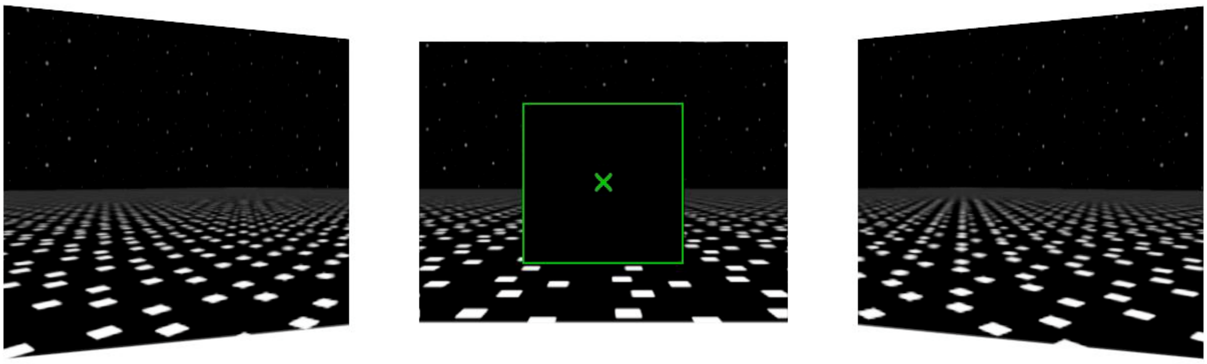

Figure 2. The virtual environment with ground and horizon presented on the display surfaces.

The height position of the display configuration is adjusted so that a horizontally positioned horizon line of the stimuli is at eye level, and the distances from observer's eyes to display surfaces are controlled to ensure accurate visual fields that the displays subtend. The participant is told to keep as still as possible while positioned in the "Sharpened Romberg Stance" and fixating the display center during the presentation trials. The employed stance is an erect stance with one foot in front of the other heel to toe, hands placed on the chest, and with the center of gravity kept approximately between the feet.

Figure 3 illustrates the geometrical axes for some postural instability measures in relation to observer position. For the postural instability measures we use the mean change computed from the registered changes in each roll (or bank) motion sequence – from start of roll to back to horizontal.

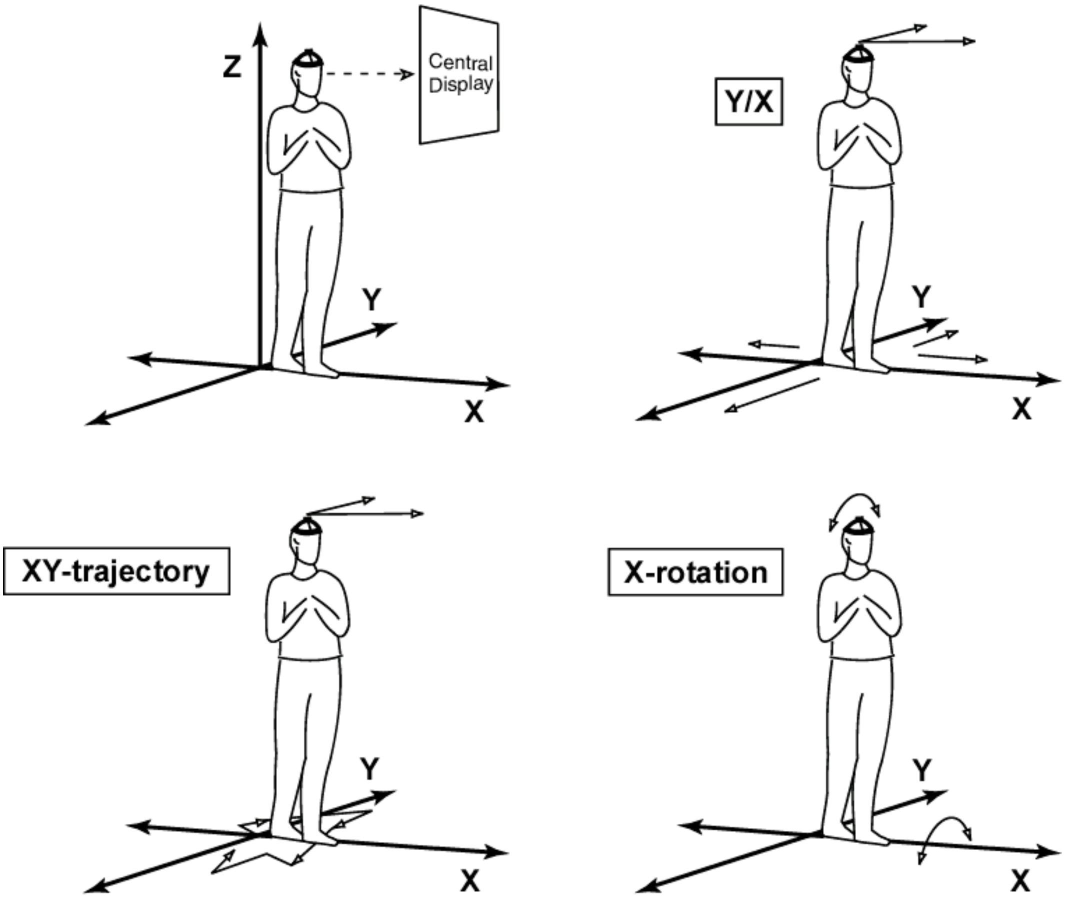

Figure 3. The geometrical axes for measures of postural instability in relation to observer position.

We expect that this method will provide us with results for extracting some display design guidelines regarding efficiency in resonating with the mechanism for spatial orientation. Further measures of performance, especially evaluation of aircraft maneuvering, with variations of such a visual interface are under planning, and these have to include experimental environments with both fixed and moving platforms. The intention is to use the Dynamic Flight Simulator here as well. Thus, again, we try to optimize a visual interface in the laboratory for later evaluation in a moving platform where the g-force can be varied.

Examples of implementation

In part building on experimental results from using the method, some basic illustrations of examples of implementation on HUD and peripheral HMDs are presented in Figure 4. These examples show an inside-out representation on both HUD and HMDs, as well as a combination of an outside-in HUD symbology with an inside-out format of artificial horizon with ground on HMDs.

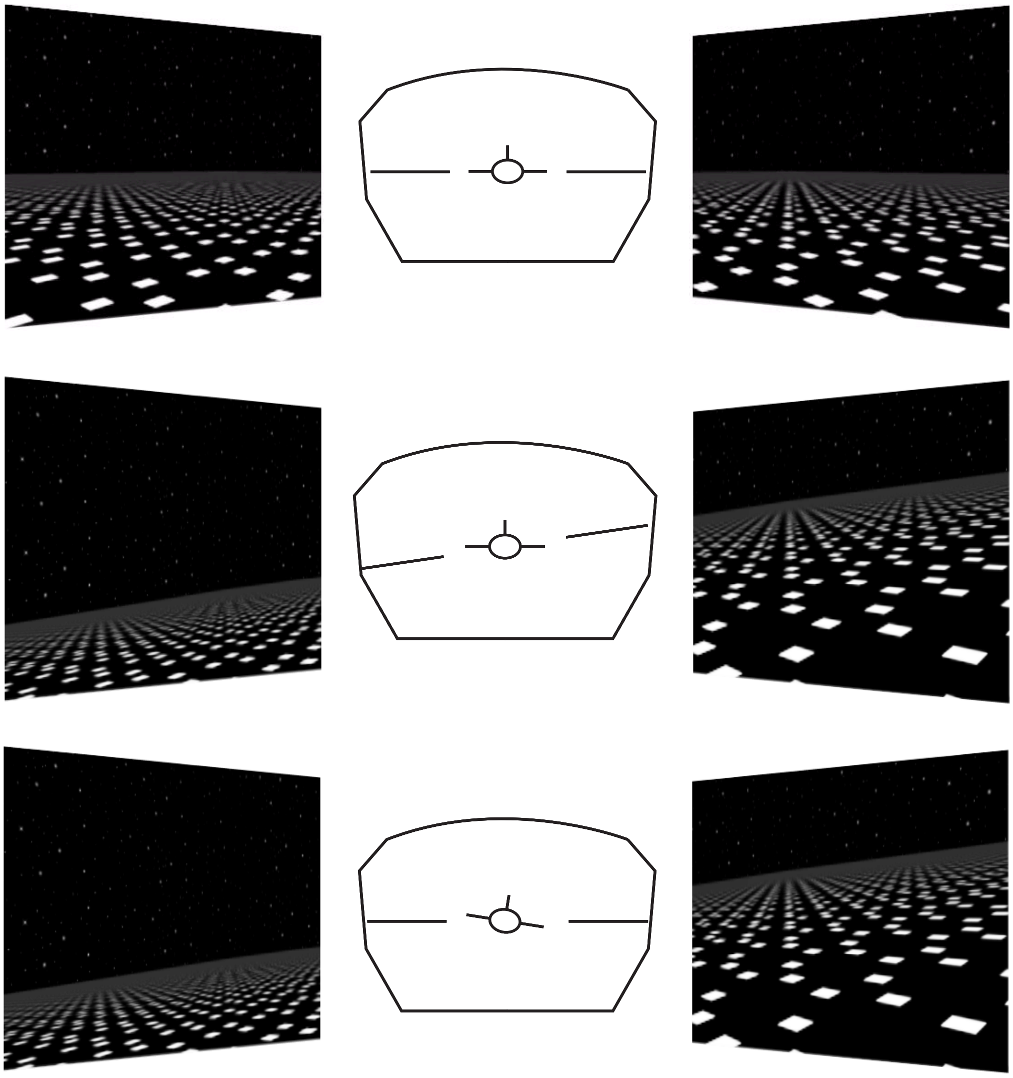

Figure 4. Illustrations of some schematic implementations from top to bottom: A “neutral” horizontal position with peripheral HMDs and a central HUD symbology, inside-out representations on both HUD and HMDs, and an outside-in format on HUD with inside-out HMDs.

Concluding remarks

The experiments have so far shown that decreasing the peripheral field down to 105° horizontally does not decrease the effectiveness of an ambient display for spatial orientation. Neither does the omission of a central area as large as 20° x 20° decrease the effectiveness of it. This means that such a display does not interfere with the task of keeping up with the various HDDs.

The spatial orientation displays could either be implemented as peripheral HMDs or HUDs. Both kinds of implementations pose problems that have to be solved before the display will be effective. The display has to provide the pilot with a simplified but correct view of the orientation of the outside world relative to the aircraft and how it changes over time. To be anchored in the outside world means that a HMD has to fully compensate for head movements of the pilot in addition to showing the movements of the aircraft. A HUD could be implemented on the sides of the cockpit. It has to compensate for any movements of the pilot relative to the cockpit in addition to showing the movements of the aircraft. In other words, if the pilot moves to the left more of the virtual world on the left side of the cockpit should be visible and less of the world on the opposite side in the same way as in a situation with good visibility. The choice of the mode of presentation has to be guided by the criteria of robustness, reliability and simplicity.

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Perception de la verticale avec un cadre visuel solidaire de la tête : implications pour la conception des afficheurs de casques en aéronautique

(Perception of the Vertical With a Head-Mounted Visual Frame: Implication for the Design of Helmet-Mounted Displays in Aeronautics)

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Une partie des travaux rapportés dans ce manuscrit a été réalisée au Centre de Recherche du Service de Santé de Armées Emile Parde (La tronche, France) en collaboration avec le Médecin Chef Christian Raphel et son équipe.

Résumé

Les travaux présentés visent à déterminer si inclure des références visuelles solidaires des mouvements de la tête, une possibilité offerte par les afficheurs de casque, peut influencer la perception de l'orientation d'un objet visuel. Une première expérience étudie l'influence d'un cadre visuel céphalocentré sur la verticale subjective, lors d'inclinaison de la tête dans le plan frontal. Elle montre qu'incliner la tête avec le cadre visuel provoque des modifications conséquentes de l'estimation de la verticale dans la direction de l'inclinaison. Ces erreurs ne peuvent pas être expliquées par une addition des erreurs imputables au cadre visuel et à l'inclinaison de la tête lorsque les effets des deux perturbations sont évalués indépendamment. De plus, la vision du cadre visuel céphalocentré pendant le mouvement ne réduit pas l'erreur, ce qui contraste avec la diminution des erreurs observée lorsque le cadre visuel est dissocié de la tête. Une seconde expérience compare la verticale subjective et la performance dans une tâche de réorientation de la tête lors d'inclinaisons du corps entier. Les estimations de la verticale se font en présence soit d'un cadre visuel céphalocentré, soit d'un cadre solidaire des mouvements du tronc mais dissocié de la tête. Les résultats montrent qu'un cadre visuel céphalocentré modifie les comportements d'orientation de la tête, ce qui contribue à augmenter significativement les erreurs d'estimation de la verticale générées par le cadre. Les deux études mettent l'accent sur le rôle fondamental du référentiel céphalocentré dans le traitement des informations visuelles pour la perception de l'orientation spatiale. Elles suggèrent qu'entourer des indicateurs d'attitude par des informations visuelles solidaires de la tête dans les afficheurs de casque pourrait contribuer à la désorientation spatiale, en particulier durant les vols de nuit.

Communication présentée lors du symposium RTO HFM sur la « Désorientation spatiale dans les véhicules militaires : causes, conséquences et remèdes », organisé à La Coruña, en Espagne, du 15 au 17 avril 2002, et éditée dans RTO-MP-086.

Les afficheurs de casque suscitent beaucoup d'intérêt chez les chercheurs et les concepteurs dans le domaine de l'aviation de combat, car il s'agit là d'outils qui ouvrent de nouvelles perspectives dans la façon de présenter des informations au pilote. La technique consiste à superposer des informations visuelles au monde réel en les projetant sur la visière du casque. Elle a l'avantage de permettre la présentation d'informations visuelles solidaires des mouvements de la tête, de façon à ce que ces informations restent constamment disponibles dans le champ de vision du pilote quelle que soit l'orientation de sa tête. Le pilote n'a donc pas besoin de quitter des yeux l'environnement externe pour se référer aux instruments de bord. L'application principale à l'heure actuelle a été de transférer le système de visée dans les afficheurs de casque, ce qui leur donne le potentiel de transformer fondamentalement les paramètres du combat aérien. Au-delà du système de visée, les progrès technologiques font envisager aux concepteurs d'inclure d'autres indicateurs dans les afficheurs de casque, y compris des indicateurs de l'attitude de l'avion. Ces indicateurs sont susceptibles eux aussi d'être asservis à l'orientation de la tête (Cohen et al., 2001).

Considérons maintenant l'exemple d'un concepteur d'afficheurs de casque qui désirerait fournir au pilote, dans la visière du dispositif, une série d'indications qui peuvent être utiles lorsque le pilote quitte des yeux les instruments du cockpit pour explorer l'environnement extérieur. Une façon de présenter ces indications sans obstruer le champ de vision du pilote pourrait consister à les disposer parallèlement à l'axe vertical de la tête, de chaque côté de la visière. Cette solution reviendrait à inclure des informations visuelles orientées, attachées à la tête, qui s'inclineraient par rapport à la verticale dès lors que l'utilisateur de l'afficheur de casque inclinerait lui-même sa tête. Or, un cadre visuel incliné peut provoquer des erreurs considérables dans une tâche d'estimation de la verticale. L'erreur est commise dans la direction de l'inclinaison du cadre visuel, ce qu'on appelle classiquement l'effet cadre (Witkin et Asch, 1948). La désorientation induite par le cadre est susceptible d'être potentialisée par l'inclinaison de la tête (Di Lorenzo et Rock, 1982).

De plus, pour percevoir correctement l'orientation d'un objet visuel dans l'espace, le système nerveux central doit transposer l'information rétinienne dans un référentiel géocentré, défini par la direction de la gravité. De nombreux auteurs s'accordent à dire que s'orienter dans le référentiel gravitaire implique une chaîne de transformation de coordonnées impliquant des sources variées d'informations (Howard, 1986). La projection de l'image sur la rétine doit être encodée et mise en rapport avec l'orientation des yeux dans leur orbite, ce qui implique la prise en compte des signaux de position des yeux. Les informations vestibulaires doivent également être considérées, puisqu'elles renseignent sur l'orientation et les déplacements de la tête. Enfin, l'information propriosomesthésique utilisée pour réguler la posture fournit le lien entre la position de la tête dans l'espace et les forces de contact du corps au sol (Mergner & Rosemeier, 1998). En d'autres termes, l'orientation d'un objet visuel par rapport à la gravité est obtenue par la transposition des coordonnées rétiniennes dans un référentiel géocentré en passant par des étapes intermédiaires définies dans des référentiels centrés sur la tête ou sur le tronc. Au regard de ces considérations sur la construction des référentiels spatiaux, la présentation d'informations visuelles solidaires des mouvements de la tête met l'utilisateur d'un afficheur de casque face à une situation inhabituelle. En effet, lorsque le pilote bouge la tête, les informations visuelles ajoutées bougent dans l'espace extra-personnel tout en restant fixes dans le référentiel de la tête. Cette configuration d'informations n'a pas d'équivalent dans des conditions naturelles. En effet, les coordonnées relatives d'un objet visuel par rapport à la tête varient habituellement dès lors que la tête (ou l'objet observé) bouge dans l'espace. Cela implique que le système nerveux central n'a probablement pas évolué pour traiter des références visuelles solidaires des mouvements de la tête et pourrait donc être amené à résoudre un conflit informationnel.

Le but du travail rapporté ici est d'évaluer les modifications éventuelles de la perception de l'orientation d'un indicateur visuel que pourrait provoquer l'inclusion dans les afficheurs de casque de références visuelles solidaires des mouvements de la tête. Les deux expériences présentées ici étudient l'influence sur la verticale subjective d'un cadre visuel céphalocentré, lorsque la tête ou le corps entier du sujet est incliné en roulis. L'obtention d'un cadre incliné d'une amplitude identique à celle de la tête a été rendue possible par l'utilisation d'un casque vidéo. Porter cet appareil donne la sensation de voir un écran céphalocentré rectangulaire dont les contours sont clairement visibles. Ainsi, quelle que soit l'orientation de la tête du sujet, l'axe vertical de symétrie du cadre reste constamment aligné avec l'axe vertical de la tête. La première expérience s'intéresse tout d'abord à l'influence du port d'un tel dispositif sur la verticale subjective lors d'inclinaisons de la tête, chez des sujets assis. La seconde expérience étudie quant à elle les effets du même type de cadre visuel sur le comportement de réorientation de la tête des sujets et sur leur perception de verticalité lorsque le corps entier est incliné.

Expérience 1 : Effets d'un cadre visuel céphalocentré sur la verticale subjective lors d'inclinaisons de la tête

Le premier objectif de l'expérience 1 vise à décrire les effets d'un cadre visuel céphalocentré sur la verticale visuelle, et ceci pour l'ensemble des inclinaisons possibles de la tête. L'influence de l'inclinaison de la tête en l'absence de référence visuelle, ainsi que l'influence d'un cadre visuel incliné, fixe dans l'espace et sans inclinaison de tête, sont également évaluées dans des conditions très similaires. La méthode utilisée se distingue de celles employées dans les études antérieures en ce qu'elle permet un positionnement libre de la tête à des inclinaisons variées en amplitudes. L'orientation de la tête et son maintien ne dépendent donc pas des dispositifs assez contraignants habituellement utilisés. De plus, la verticale visuelle est estimée pour un grand nombre d'amplitudes d'inclinaisons du cadre et/ou de la tête. Les analyses de régression effectuées sur ces valeurs permettent d'obtenir des fonctions psychométriques précises. Dans ces conditions, il est possible de déterminer si les effets d'un cadre fixe par rapport à la tête lors d'inclinaisons de la tête peuvent s'expliquer par l'addition d'un effet cadre et d'un effet postural ou, dans le cas contraire, de préciser quelle est la nature des pondérations sensorielles mises en jeu dans ces conditions. Afin d'évaluer l'influence potentielle de la commande motrice associée à la production volontaire d'inclinaisons de la tête, l'expérience compare également les estimations obtenues de la verticale à la suite de mouvements actifs et passifs de la tête.

Le second objectif de l'expérience consiste à évaluer l'influence de la vision continue ou discontinue des cadres visuels lors de leurs changements d'orientation. L'orientation du cadre solidaire de la tête ne peut être évaluée que sur la base des signaux de position de la tête, puisque son orientation ne change jamais par rapport au segment céphalique. En d'autres termes, les transformations de coordonnées visuelles dans le référentiel céphalocentré sont inexistantes. Au contraire, lorsque l'orientation du cadre est dissociée de celle de la tête, toute rotation peut être référée à la tête. Ainsi, quand le sujet a la possibilité de garder les yeux ouverts pendant la rotation, les variations d'orientation du cadre par rapport à la tête peuvent être prises en compte en conjonction avec les signaux vestibulaires et proprioceptifs qui renseignent sur l'orientation de la tête dans l'espace. Nous faisons donc l'hypothèse que la vision du cadre lors de ses rotations dans l'espace ne diminue les effets observés sur la verticale visuelle que lorsque l'orientation du cadre est dissociée de celle de la tête.

Méthodes

Douze sujets, 9 hommes et 3 femmes, âgés de 23 à 41 ans, se sont portés volontaires pour cette expérience. Aucun sujet n'a déclaré souffrir ou avoir souffert de troubles vestibulaires. Leur vision était normale ou normalement corrigée.

L'expérience a été réalisée dans l'obscurité. Tous les sujets ont participé à 8 conditions expérimentales. Dans chacune d'elles, la tâche était de placer une baguette lumineuse à la verticale. La baguette visuelle, de couleur blanche, était de forme oblongue, d'une longueur de 10° d'angle et d'une largeur de 2° en son milieu. La baguette pouvait tourner autour de son axe central en agissant sur une manette de jeux placée sur l'accoudoir droit du siège. Aucune limite temporelle n'était fixée pour estimer la verticale. Cependant, les consignes insistant sur la nécessité d'effectuer la tâche en première impression, rares ont été les ajustements excédant 5 secondes. A chaque nouvel essai, l'orientation initiale de la baguette était déterminée de façon aléatoire. Chaque condition expérimentale comportait 40 essais.

La baguette lumineuse utilisée pour les estimations de la verticale était générée soit sur un moniteur informatique de 17", soit sur un casque vidéo (Glasstron PLM-S700 commercialisé par Sony) selon les conditions expérimentales (Fig. 1).

Conditions «tête et cadre inclinés» (TCI)

Dans les conditions TCI, les sujets portaient un casque vidéo qui donne la sensation de voir un écran informatique, centré sur l'axe interoculaire, d'une taille angulaire de 30° X 22,5°. L'écran virtuel apparaît comme un rectangle gris foncé sur un arrière plan totalement noir. Ce contraste de luminosité forme donc un contour perçu par les sujets comme un cadre visuel. Un récepteur magnétique (Polhemus Fastrak) était fixé sur le haut du crâne, pour mesurer l'orientation de la tête et du casque. Les sujets, équipés du casque vidéo, plaçaient leur tête à diverses orientations dans le plan frontal (Fig. 1A). Le cadre virtuel et la tête étaient donc inclinés de façon identique par rapport à la gravité. Le premier essai était toujours réalisé avec la tête droite. Ensuite, une nouvelle orientation de la tête était choisie et maintenue le temps d'estimer la verticale. Immédiatement après la validation de la mesure, une nouvelle posture de la tête était adoptée.

Quatre conditions TCI ont été réalisées. Dans deux d'entre elles, les sujets bougeaient la tête volontairement et choisissaient eux-mêmes l'amplitude de l'inclinaison. Les sujets avaient pour instruction d'explorer l'ensemble des inclinaisons possibles de la tête, dans un ordre pseudo-aléatoire au cours des 40 essais. Dans les deux conditions TCI restantes, la tête était inclinée d'une orientation à une autre par l'expérimentateur. Les sujets avaient pour consigne de ne pas résister au mouvement imposé par l'expérimentateur et, à l'opposé, de ne pas accompagner le mouvement. Pour chaque type de mouvement (actif et passif), deux conditions ont été réalisées. Dans l'une d'elle, les sujets fermaient les yeux pendant le mouvement alors que dans l'autre, ils voyaient le cadre tout en bougeant.

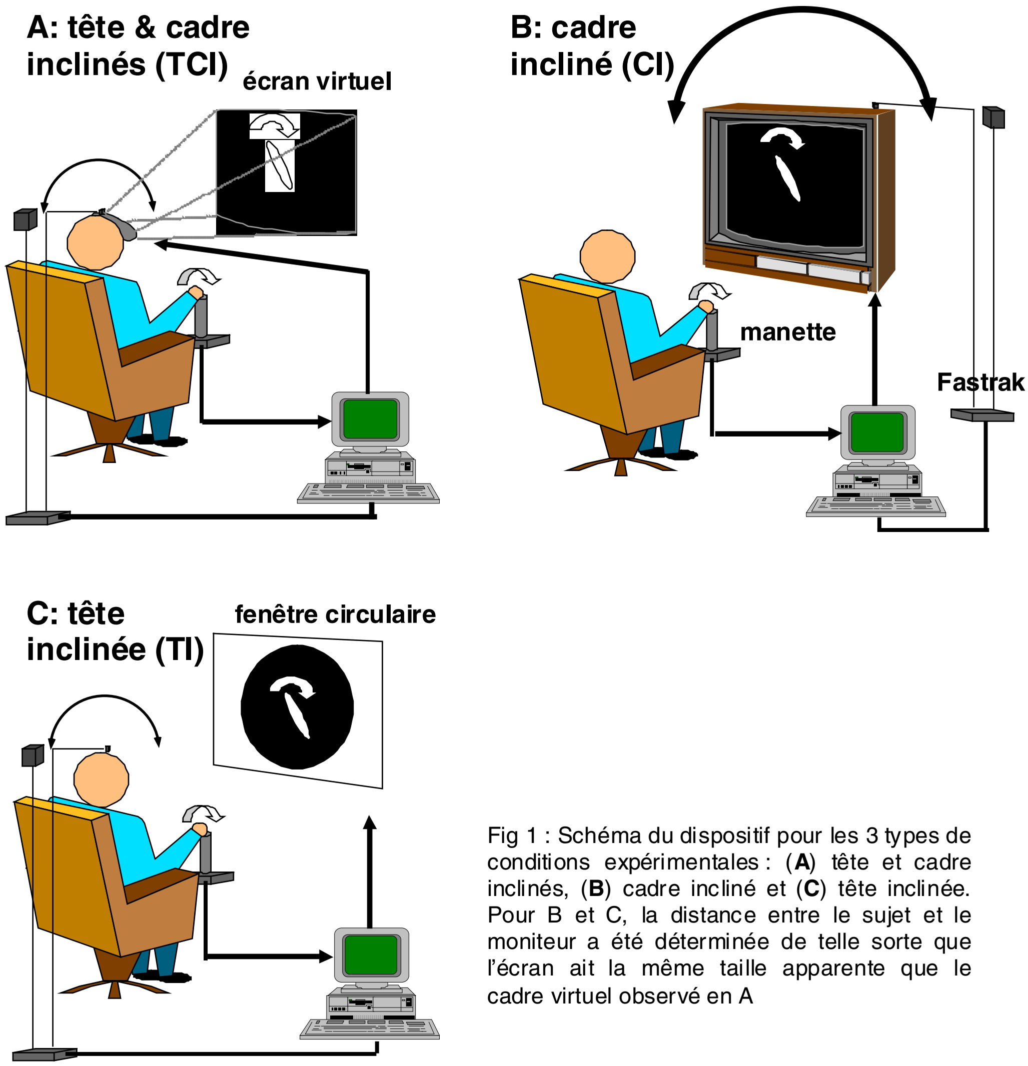

Fig 1 : Schéma du dispositif pour les 3 types de conditions expérimentales : (**A**) tête et cadre inclinés, (**B**) cadre incliné et (**C**) tête inclinée. Pour B et C, la distance entre le sujet et le moniteur a été déterminée de telle sorte que l'écran ait la même taille apparente que le cadre virtuel observé en A

Conditions «cadre incliné» (CI)

La baguette était cette fois présentée sur un moniteur 17", fixé sur une plate-forme qui pouvait être inclinée manuellement dans le plan frontal. Un récepteur magnétique était monté sur le moniteur afin d'enregistrer son orientation. Les contours de l'écran formé par l'ensemble des pixels formaient un cadre rectangulaire lumineux. Afin d'ajuster au mieux la distance entre le sujet et l'écran, le casque vidéo décrit précédemment était superposé à l'écran du moniteur (le casque était utilisé dans ce cas en mode «see through», qui permet de superposer l'écran virtuel au monde extérieur visible). Seuls les contours du cadre et la barre lumineuse étaient visibles dans un environnement totalement noir par ailleurs.

Deux conditions CI ont été réalisées. Cette fois, la tête était maintenue droite par une sorte de minerve. L'expérimentateur changeait l'orientation du cadre en agissant sur la plate-forme inclinable (Fig. 1B). Chaque nouvelle orientation était choisie au hasard entre 40° dans le sens anti-horaire et 40° dans le sens horaire. Dans l'une des conditions, les sujets avaient pour consigne de fermer les yeux entre les essais afin de ne pas disposer de la vision du cadre lorsque celui-ci était en rotation. Dans l'autre condition, la vision continue du cadre était permise.

Conditions «tête inclinée» (TI)

De la même manière que durant les conditions TCI, les sujets avaient pour instruction de positionner leur tête dans 40 orientations différentes et d'estimer la verticale pour chacune des positions (Fig. 1C). La baguette était affichée sur l'écran utilisé dans les conditions CI, placé à la même distance, mais cette fois les références visuelles orientées fournies par le contour de l'écran étaient supprimées. A cette fin, un panneau noir, percé en son centre d'un orifice circulaire de 15° d'angle, était disposé devant le moniteur. La baguette apparaissait au centre de la fenêtre circulaire.

Résultats

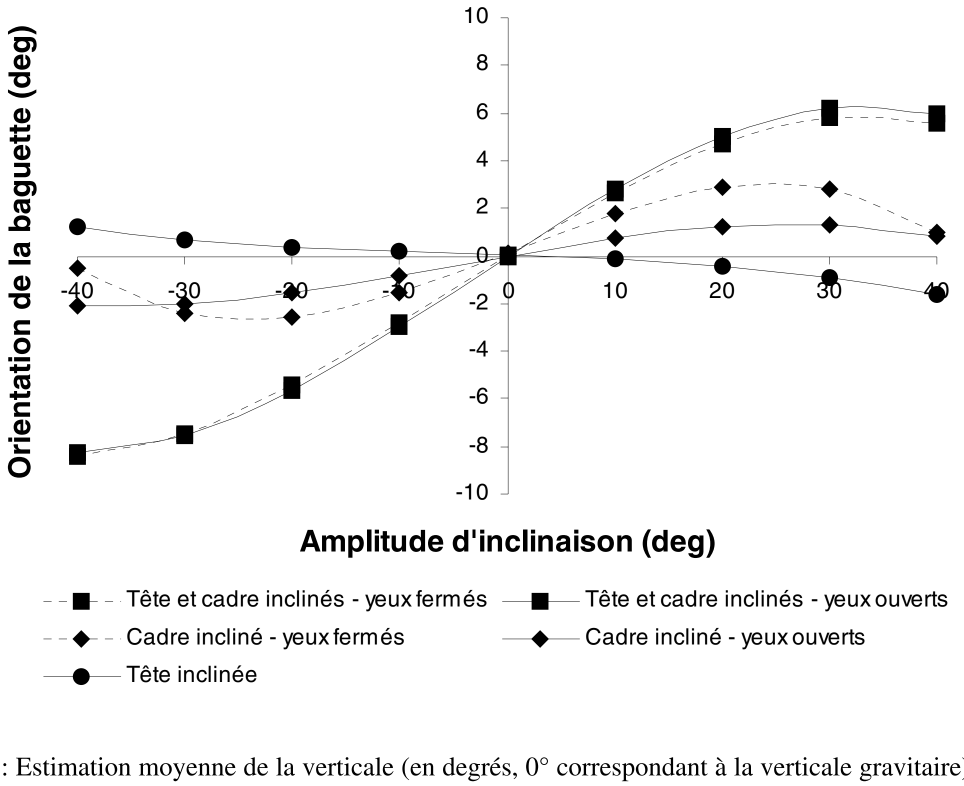

Fig. 2 : Estimation moyenne de la verticale (en degrés, 0° correspondant à la verticale gravitaire) en fonction de l'angle d'inclinaison de la tête et/ou du cadre dans toutes les conditions.

Toutes les conditions expérimentales ont généré une variabilité interindividuelle importante, une caractéristique très souvent retrouvée dans les études portant sur la verticale subjective. Cette variabilité s'observe sur l'amplitude des erreurs d'estimation de la verticale, mais aussi sur la forme des fonctions psychométriques obtenues. En effet, les erreurs commises en estimant la verticale étaient, pour la plus grande partie des sujets, une fonction linéaire de l'inclinaison de la tête et/ou du cadre pour atteindre un maximum vers 25° d'inclinaison ou plus. Pour des inclinaisons supérieures, l'erreur cessait d'augmenter, voire diminuait. D'autres sujets, au contraire, présentaient des réponses purement linéaires. C'est pourquoi les données ont été analysées à l'aide de régressions polynomiales de 3ème ordre. Puisque toutes les courbes de réponses pouvaient être résumées en grande partie par leur composante linéaire, la pente des courbes à l'origine est la valeur pertinente pour estimer la force de l'effet (erreur constante). De plus, l'erreur variable a été évaluée en calculant la moyenne des résidus absolus (les valeurs absolues des différences entre les valeurs observées et les valeurs prédites pour un même angle d'inclinaison).

Les jugements de la verticale ont des profils superposables, que les mouvements de tête aient été réalisés activement ou passivement. Cette observation est valable dans les conditions TCI (t_{11} = 0,90 avec les yeux ouverts et t_{11} = 0,64 avec les yeux ouverts) et dans les conditions TI (t_{11} = 0,10). Par conséquent, les données ont été moyennées et les analyses ultérieures ont été réalisées sur ces moyennes. La figure 2 présente les courbes de réponses moyennes obtenues dans l'ensemble des conditions. On observe que, dans les conditions TCI, l'erreur d'estimation de la verticale correspond à 29% et 28% de l'inclinaison de la tête et du cadre, respectivement lorsque les yeux sont ouverts et fermés. Dans les conditions CI, l'erreur de 17% commise avec les yeux fermés chute à 8% lorsque les sujets ont la possibilité d'observer les rotations du cadre visuel. Enfin, incliner la tête en l'absence de référence visuelle ne produit qu'un très léger effet Müller (inclinaison de la verticale visuelle dans le sens opposé à l'inclinaison de la tête), non significatif.

Une analyse de variance à mesures répétées 2 (cadre fixe par rapport à la tête *vs.* cadre dissocié de la tête) x 2 (yeux fermés *vs.* yeux ouverts) réalisée sur les pentes des courbes met en évidence un effet principal du type de cadre [$F(1,11) = 5,96$; $p<.05$], une absence d'effet principal de la vision du cadre pendant la rotation [$F(1,11) = 4,15$] et une interaction significative entre les deux variables [$F(1,11) = 12,76$; $p<.005$]. Les analyses post-hoc (tests de Newman-Keuls) révèlent que l'interaction est la conséquence d'un effet significatif de la vision continue du cadre dans les conditions CI (la pente est plus forte avec les yeux fermés, $p<.001$), mais pas dans les conditions TCI [$p>.50$].

Les erreurs commises dans les conditions TCI sont plus grandes que la somme des erreurs obtenues dans les conditions CI et dans les conditions TI. Cet effet est significatif avec les yeux fermés pendant le mouvement ($t_{11} = 2,96$; $p<.05$) et encore plus avec les yeux ouverts ($t_{11} = 6,65$; $p<.001$).

Les résidus absolus moyens diffèrent selon les conditions expérimentales [$F(2,22) = 9,99$; $p<.001$]. Les analyses post-hoc révèlent que la variabilité intraindividuelle est plus faible dans les conditions CI que dans les conditions TCI ($p<.001$) et que dans les conditions TI ($p<.01$). La différence entre les deux dernières conditions n'atteint pas le niveau de significativité ($p<.15$). Aucune autre manipulation expérimentale (yeux fermés/yeux ouverts, mouvements actifs/mouvements passifs) n'a d'effet significatif sur la variabilité de la réponse. La figure 3 décrit les résidus absolus moyens en fonction de l'inclinaison. Lorsque la tête est droite (conditions CI), les résidus restent presque constants, quelle que soit l'orientation du cadre. Au contraire, la variabilité augmente avec le degré d'inclinaison de la tête. Ce profile est frappant, particulièrement lorsque l'inclinaison de la tête est combinée avec un cadre visuel incliné (conditions TCI).

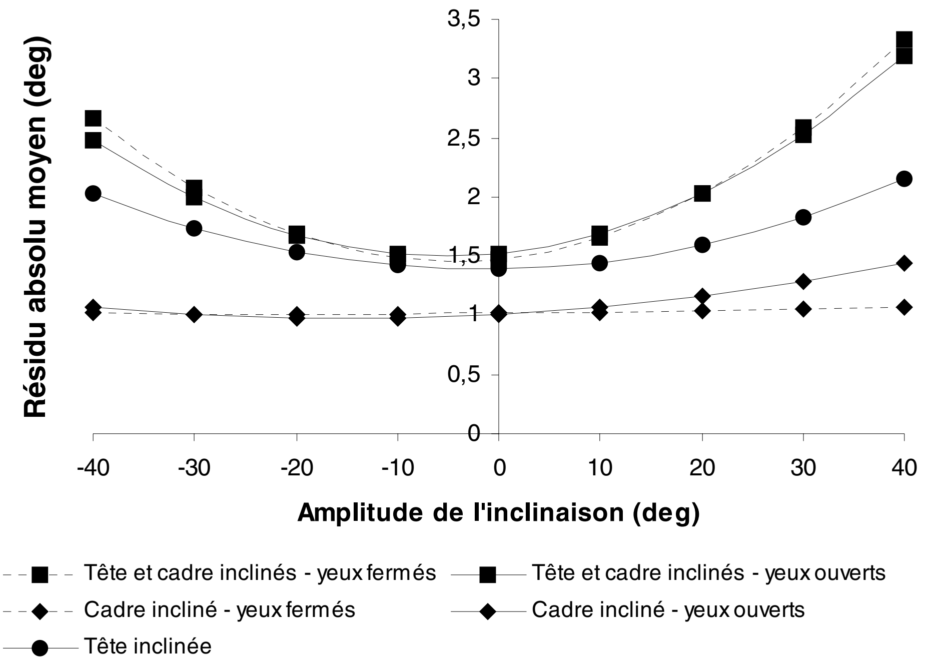

Fig. 3 : Distribution des résidus absolus moyens (variabilité de la réponse) en fonction de l'inclinaison dans toutes les conditions.

Discussion

L'expérience 1 s'intéresse aux effets d'un cadre visuel solidaire de la tête sur la verticale visuelle lorsque la tête est inclinée. Les effets d'une telle combinaison d'informations ont été comparés aux effets simples de l'inclinaison d'un cadre fixe dans l'espace et à ceux de l'inclinaison de la tête en l'absence de références visuelles orientées. Les inclinaisons du cadre et/ou de la tête ont été variées de façon systématique afin de pouvoir décrire précisément la forme des fonctions psychométriques résultantes. Deux résultats principaux peuvent être mis en avant. Premièrement, les erreurs dans l'estimation de la verticale sont nettement plus grandes lorsqu'un cadre visuel s'incline avec la tête que lors d'inclinaisons similaires d'un cadre fixe dans l'espace sans inclinaison de tête. L'augmentation de l'effet du cadre visuel ne peut pas être expliqué par l'addition d'un effet postural, puisque incliner la tête en l'absence de références visuelles n'influence pas, en moyenne, l'estimation de la verticale faite par les sujets. Deuxièmement, la vision continue du cadre lors de ses changements d'orientation n'améliore la performance des sujets que lorsque la tête et le cadre sont dissociés, c'est-à-dire avec un cadre fixe dans l'espace.

Réfutation de l'hypothèse d'additivité des effets visuels et posturaux

Dans la grande majorité des expériences, les effets induits par les stimulations visuelles sont nettement plus importants lorsque la tête est inclinée par rapport à la gravité que lorsqu'elle est maintenue droite (Dichgans et al., 1974 ; Witkin et Asch, 1948). Le débat est encore ouvert pour savoir si l'augmentation de la désorientation relève d'une addition des effets posturaux et des effets visuels ou si les deux effets sont interdépendants. Selon le modèle additif, l'erreur due à l'inclinaison de la tête ou du corps entier s'ajouterait intégralement aux erreurs provoquées par la perturbation visuelle. Autrement dit, la réponse fournie par le sujet lorsque les deux perturbations sont combinées serait le résultat de l'addition vectorielle des deux verticales perçues dans les situations où une seule manipulation expérimentale est réalisée. Pour le modèle interdépendant, l'influence de la vision sur la perception de l'orientation spatiale est limitée par le rôle inhibiteur des utricules et des informations somatosensorielles lorsque ceux-ci ne détectent aucun changement dans l'information gravitaire. Lorsque la tête est inclinée, la fiabilité des afférences otolithiques diminuerait et, par conséquent, la pondération des différentes sources d'informations serait modifiée en faveur des afférences visuelles. Récemment, Guerraz et al. (1998b) ont examiné la combinaison d'inclinaisons de la tête et de perturbations visuelles statiques (cadre incliné). Ils concluent que l'augmentation de l'effet cadre observée dans ces conditions ne serait que la conséquence d'un effet postural de type Aubert (erreur d'estimation dans la direction de l'inclinaison corporelle), ce qui contredit les conclusions de DiLorenzo et Rock (1982).

Les résultats de l'expérience 1 ne soutiennent pas l'hypothèse d'additivité, puisque nos sujets ont montré une influence du cadre visuel nettement accrue, sans effet Aubert. D'un point de vue plus général, il est difficile d'envisager la fusion des informations sensorielles provenant de différentes sources comme relevant d'une simple sommation. En effet, il existe la plupart du temps de grandes différences dans les caractéristiques spatiales et temporelles des systèmes sensoriels (Howard, 1997). Les modèles actuels essaient d'ailleurs d'expliquer l'intégration d'afférences sensorielles multiples en terme de combinaisons non-linéaires (Mergner et al., 1997, 1998). En fonction des conditions, une modalité sensorielle peut prévaloir sur une autre ou, au contraire, voir son influence diminuer. Plus spécifiquement, les signaux de position de la tête semblent n'être fiables que lorsqu'ils sont intégrés au travers de processus dynamiques (Teasdale et al., 1999). Par conséquent, lorsque la tête est inclinée et maintenue dans une orientation donnée, l'augmentation des erreurs dans la direction du cadre incliné reflète probablement un poids plus important affecté aux références visuelles.

La désorientation spatiale : un phénomène à deux visages

L'étude de la variabilité de la réponse des sujets suggère également une fiabilité moindre des signaux de position de la tête lorsque celle-ci est inclinée. La variabilité intraindividuelle est faible lorsque la tête est droite, quelle que soit l'orientation du cadre visuel. En revanche, la variabilité est plus grande dès lors que la tête est inclinée et elle s'accroît avec l'amplitude d'inclinaison, que les références visuelles soient absentes ou fixes par rapport à la tête. Il est intéressant de remarquer que cette observation quantitative correspond aux commentaires des sujets, qui ont exprimé une plus grande difficulté à réaliser la tâche lorsque la tête était inclinée, en particulier en combinaison avec le cadre visuel. Dans ces dernières conditions, les sujets ont d'ailleurs souvent rapporté un fort sentiment d'incertitude quant à la précision de leurs ajustements. Ces résultats mettent l'accent sur le fait que la désorientation spatiale peut être définie de deux façons différentes. D'une part, l'erreur constante par rapport à la verticale gravitaire témoigne du résultat perceptif élaboré par le système nerveux central, en fonction des informations dont il dispose. En l'occurrence, lorsque le cerveau doit s'accommoder d'informations appauvries ou conflictuelles, la perception peut être biaisée en faveur d'une modalité sensorielle ou d'une autre. D'autre part, on peut considérer l'erreur variable qui atteste du niveau de reproductibilité de la réponse du sujet. En ce qui concerne les estimations subjectives, cette reproductibilité reflète souvent le niveau de confiance du sujet dans sa réponse. Dans ce cas, désorientation spatiale n'est pas nécessairement synonyme d'altération de performance moyenne. Nos résultats illustrent cette distinction. En effet, le biais perceptif atteint un plateau et décroît parfois (Fig. 2), alors que la variabilité (et sa contrepartie subjective) continue à augmenter avec l'amplitude de l'inclinaison de la tête (Fig. 3).

Traitement de l'information visuelle en mouvement dans le référentiel céphalocentré

Lorsqu'un cadre visuel solidaire des mouvements de la tête est porté par le sujet, la vision continue du cadre durant les inclinaisons n'améliore pas la performance finale. Dans ce cas, le système nerveux central doit composer avec des informations visuelles orientées, à la fois stables dans le référentiel céphalocentré et mobiles dans le référentiel gravitaire. En fait, l'orientation du cadre ne peut alors être appréciée que par le biais des signaux de position de la tête, c'est-à-dire grâce à l'information vestibulaire et à la proprioception du cou. La commande motrice ne semble avoir aucune influence puisque les résultats sont identiques, que les mouvements de tête soient effectués activement ou passivement. Les résultats obtenus avec le cadre solidaire de la tête contrastent nettement avec l'amélioration des jugements de verticalité apportée par la vision continue d'un cadre ancré dans l'espace extracorporel. Cette condition expérimentale se rapproche des conditions naturelles où la scène visuelle bouge dans le référentiel céphalocentré dès lors que la tête bouge ou que les éléments de l'environnement changent de position ou d'orientation. Le fait que le traitement continu de l'information visuelle ne réduise les erreurs que lorsque la tête et le cadre sont dissociés suggère que les indices visuels de mouvement doivent être intégrés dans le référentiel céphalocentré pour qu'ils puissent participer à la constance de l'orientation spatiale.

Expérience 2 : Effets d'un cadre visuel céphalocentré sur la réorientation de la tête et la verticale subjective lors d'inclinaisons corporelles

L'expérience 2 s'intéresse cette fois à l'estimation de la verticale lorsque le corps entier du sujet est incliné dans le plan frontal, en présence soit d'un cadre solidaire de l'inclinaison du tronc, soit d'un cadre solidaire des mouvements de la tête. Dans les deux cas, le sujet est assis dans un siège monté sur une plate-forme inclinable en roulis. Le cadre solidaire du corps est fourni par les contours d'un écran, fixé sur la plate-forme à hauteur des yeux du sujet. Le cadre solidaire de la tête est fourni par le casque vidéo utilisé dans l'expérience 1. Lorsque l'orientation de la tête est maintenue dans l'alignement du tronc, les deux conditions sont strictement identiques, quelle que soit l'orientation du corps par rapport à la gravité. En revanche, lorsque la tête est mobile, Les deux conditions diffèrent. En effet, si le cadre visuel est solidaire de la plate-forme, c'est-à-dire lorsqu'il s'incline avec le corps du sujet tout en restant dissocié de la tête, les mouvements de la tête produisent un déplacement du cadre relativement au référentiel céphalocentré. L'information visuelle dynamique qui est générée devrait contribuer à diminuer l'influence du cadre sur la verticale subjective. En revanche, lorsque le cadre visuel est solidaire des mouvements de la tête, bouger la tête provoque un mouvement du cadre dans le référentiel gravitaire, mais aucune variation de l'orientation du cadre dans le référentiel céphalocentré. Dans cette condition, loin d'améliorer la performance des sujets, les mouvements de la tête et du cadre visuel dans l'espace risquent de désorienter d'avantage le sujet.

L'expérience 2 étudie également l'influence des deux types de cadres visuels sur le positionnement de la tête et ses conséquences sur la perception de la verticale. A cette fin, il est demandé au sujet de repositionner sa tête dans l'alignement du tronc après avoir effectué une série de mouvements céphaliques, puis, une fois la posture adoptée, d'estimer la verticale. Là encore, on peut supposer un effet différencié des deux types de cadres visuels. En effet, certains travaux montrent que des références visuelles orientées peuvent influer sur la posture céphalique. Un cadre visuel incliné, par exemple, induit une réorientation de la tête dans la direction de l'inclinaison du cadre (Guerraz et al., 2001 ; Isableu et al., 1997 ; Sares et al., résultats non publiés). Le système nerveux central utiliserait donc l'information visuelle statique disponible dans l'environnement pour réorienter la partie supérieure du corps, avec très certainement pour finalité de faire de la tête un référentiel spatial stable et orienté adéquatement pour la perception du monde visuel (Amblard et al., 1985 ; Gresty et Bronstein, 1992).

Dans l'expérience décrite ici, le sujet a pour tâche de réorienter sa tête dans l'alignement du tronc. Or, le cadre visuel solidaire de la plate-forme et l'axe céphalocaudal du sujet (axe Z) sont colinéaires. Par conséquent, il est fort probable que, dans cette condition, les sujets tirent avantage de la présence du cadre pour mener à bien la tâche de réorientation de la tête. En revanche, le cadre visuel solidaire de la tête n'a pas d'ancrage dans l'espace extra-corporel. Son orientation ne peut être évaluée qu'à partir des signaux de position de la tête. L'information visuelle est donc présente, mais non-utilisable pour réorienter la tête. On peut donc faire l'hypothèse que le repositionnement de la tête donnera lieu a des erreurs plus importantes dans cette condition. Toute erreur de repositionnement risque d'avoir des conséquences sur l'estimation de la verticale. En effet, le cadre étant solidaire de la tête, son inclinaison dans l'espace sera modifiée de la même amplitude que l'erreur de repositionnement de la tête. L'expérience 2 vise donc à (1) quantifier les éventuelles erreurs de repositionnement de la tête en présence ou en l'absence de références visuelles ancrées dans l'espace extra-personnel, et (2) déterminer dans quelle mesure ces erreurs interagissent avec les références visuelles pour influencer la perception de la verticale.

Méthodes

Les résultats de 6 hommes et 3 femmes ont été retenus pour cette expérience. Aucun sujet n'a déclaré souffrir ou avoir souffert de troubles vestibulaires. Leur vision était normale ou normalement corrigée.

Les sujets étaient assis dans un siège baquet fixé sur une plate-forme verticale (Fig. 4). La plate-forme pouvait être inclinée dans le plan frontal autour d'un axe de rotation situé approximativement au niveau du centre de masse du sujet. Les sujets étaient fermement maintenus immobiles dans le siège par un ensemble de sangles au niveau des pieds, des jambes, du bassin, de la poitrine et des épaules. La tête pouvait également être maintenue dans l'alignement du tronc, lorsque les conditions expérimentales l'exigeaient, grâce à deux presses appuyant sur les tempes.

La baguette visuelle utilisée pour indiquer la verticale était la même que celle de l'expérience 1. La baguette était présentée soit dans le casque vidéo utilisé dans l'expérience précédente, lequel présentait un écran virtuel dont les contours fournissaient un cadre solidaire des mouvements de la tête, soit sur un écran placé fixé face au sujet sur la plate-forme (Fig. 4). Les cadres visuels formés par les bords de chaque écran avaient une taille angulaire de 30° X 22,5°. Seuls les contours de l'écran et la barre lumineuse étaient visibles dans un environnement totalement noir par ailleurs.

Un dispositif magnétique Fastrak mesurait l'orientation de la tête par rapport au tronc. L'émetteur était fixé sur la plate-forme à la droite du sujet et un récepteur était attaché à un casque ajustable, porté par le sujet.

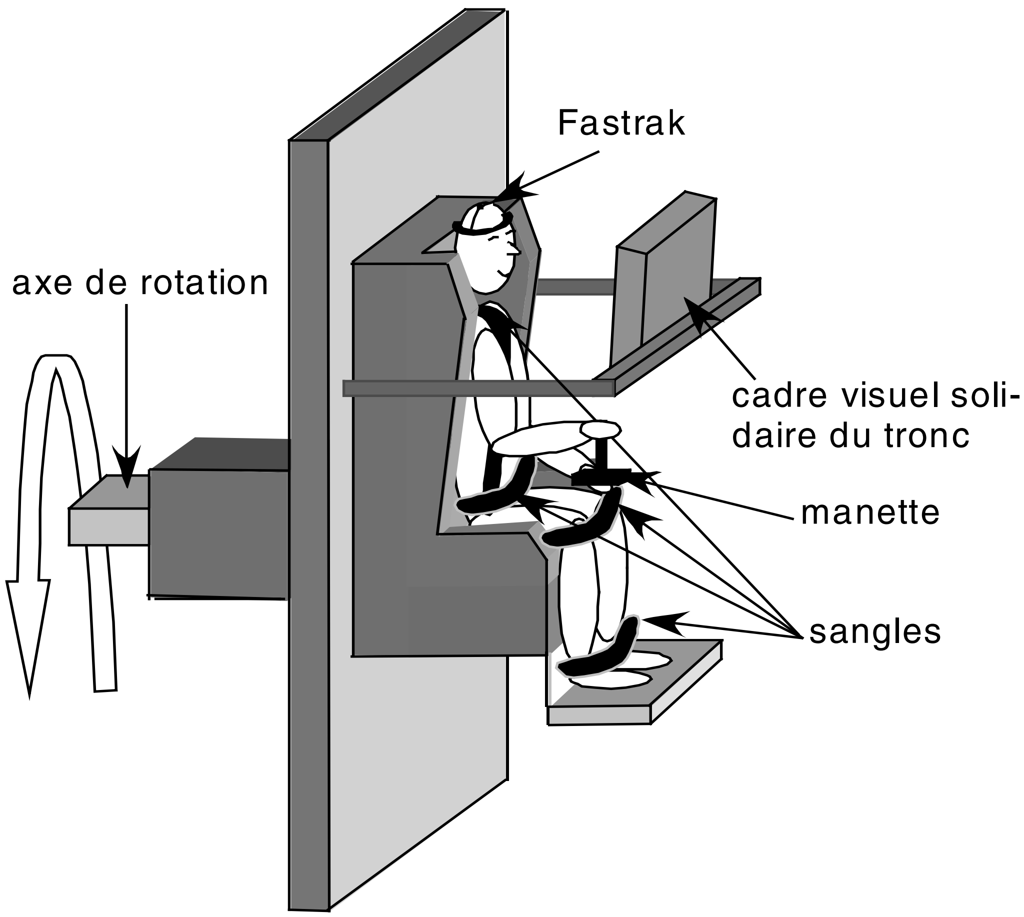

Fig. 4 : Schéma du dispositif expérimental dans la condition où le cadre visuel est solidaire du tronc (tête mobile). Dans les conditions «tête fixe», la tête est maintenue immobile dans l'axe du corps par deux presses latérales.

Inclinaisons du corps

Le corps des sujets a été incliné avec la plate-forme à 15° et 30° dans le plan frontal, dans le sens horaire et dans le sens anti-horaire. Les inclinaisons s'effectuaient avec une accélération initiale de $3°.s^{-2}$, jusqu'à une vitesse de $3°.s^{-1}$. Cette vitesse était maintenue constante jusqu'à la phase de décélération, elle aussi effectuée à $3°.s^{-2}$. Durant la rotation, les sujets avaient pour consigne de garder les yeux ouverts et de regarder le cadre visuel. Des valeurs de références ont été enregistrées avant chaque séquence d'inclinaisons, lorsque la plate-forme était verticale.

Type de cadre visuel

La baguette visuelle apparaissait au centre de trois types de cadre visuel, dont l'ordre de présentation a été contrebalancé. Le casque vidéo fournissait un cadre solidaire de la tête (conditions CST). L'axe vertical du cadre visuel restait donc constamment aligné sur l'axe vertical de la tête, quelle que soit l'orientation de celle-ci. Les contours de l'écran fixé à la plate-forme fournissaient un cadre visuel solidaire de la plate-forme (conditions CSP). L'axe vertical du cadre restait cette fois constamment aligné avec l'axe vertical du corps du sujet (axe Z). Une fenêtre circulaire entourant la baguette formait un cadre visuel non-orienté (conditions CNO).

Mobilité de la tête

Dans la moitié des conditions expérimentales, la tête du sujet était maintenue dans l'alignement du tronc par les presses latérales. Pendant la rotation et les estimations de la verticale, le sujet avait pour instruction de regarder le cadre visuel. Dans l'autre moitié des conditions expérimentales, la tête du sujet était libre. Pendant les rotations, le sujet avait pour instruction de maintenir la tête dans l'alignement du tronc. En revanche, avant d'estimer la verticale, il devait réaliser des mouvements libres de la tête pendant quelques secondes. Les mouvements devaient être effectués dans toutes les directions de l'espace, tout en gardant le regard dirigé vers le cadre visuel. Finalement, le sujet devait réorienter la tête de façon à la remettre dans l'alignement du buste et estimer la verticale.

Résultats

La figure 5 montre les estimations de la verticale dans toutes les conditions expérimentales. Pour la clarté de l'illustration et pour mieux mettre en évidence la linéarité des effets en fonction de l'inclinaison du sujet, une erreur dans l'estimation de la verticale se voit assigner une valeur positive, si elle est dans le sens horaire, et négative, si elle est dans le sens anti-horaire. Pour les analyses statistiques, en revanche, les erreurs d'appréciation de la verticale sont positives si elles sont commises dans le sens de l'inclinaison du corps (et du cadre). Les valeurs de références obtenues dans chaque condition sans inclinaison corporelle ont été retranchées à ces données.

En ce qui concerne les effets principaux, l'analyse révèle un effet significatif du type de cadre visuel [$F(2,16) = 15,96$; $p<.001$], pas d'effet de la mobilité de la tête [$F(1,8) = 0,43$], pas d'effet du côté d'inclinaison du corps [$F(1,8) = 5,15$] et un effet significatif de l'amplitude d'inclinaison [$F(1,8) = 37,73$; $p<.001$]. Parmi toutes les interactions possibles, une seule est significative. Il s'agit de l'interaction de premier ordre entre le type de cadre visuel et la mobilité de la tête [$F(2,16) = 4,72$; $p<.05$]. Les tests post-hoc effectués sur cette interaction montrent que, dans la condition CST, les erreurs augmentent de façon significative lorsque la tête est en mouvement avant l'estimation de la verticale ($p<.05$). En revanche, la réduction des erreurs observées lorsque la tête est libre n'est significative ni dans la condition CSP, ni dans la condition CNO. Si l'on considère maintenant les erreurs d'estimation de la verticale en proportion de l'amplitude d'inclinaison de la plate-forme, on observe que les erreurs commises dans les conditions CSP «tête fixe» et «tête libre» correspondent respectivement à 26% et 20% de l'inclinaison de la plate-forme. L'erreur commise en CST «tête fixe» est équivalente, puisqu'elle atteint 22%. Cette proportion augmente à 34% en CST «tête libre».

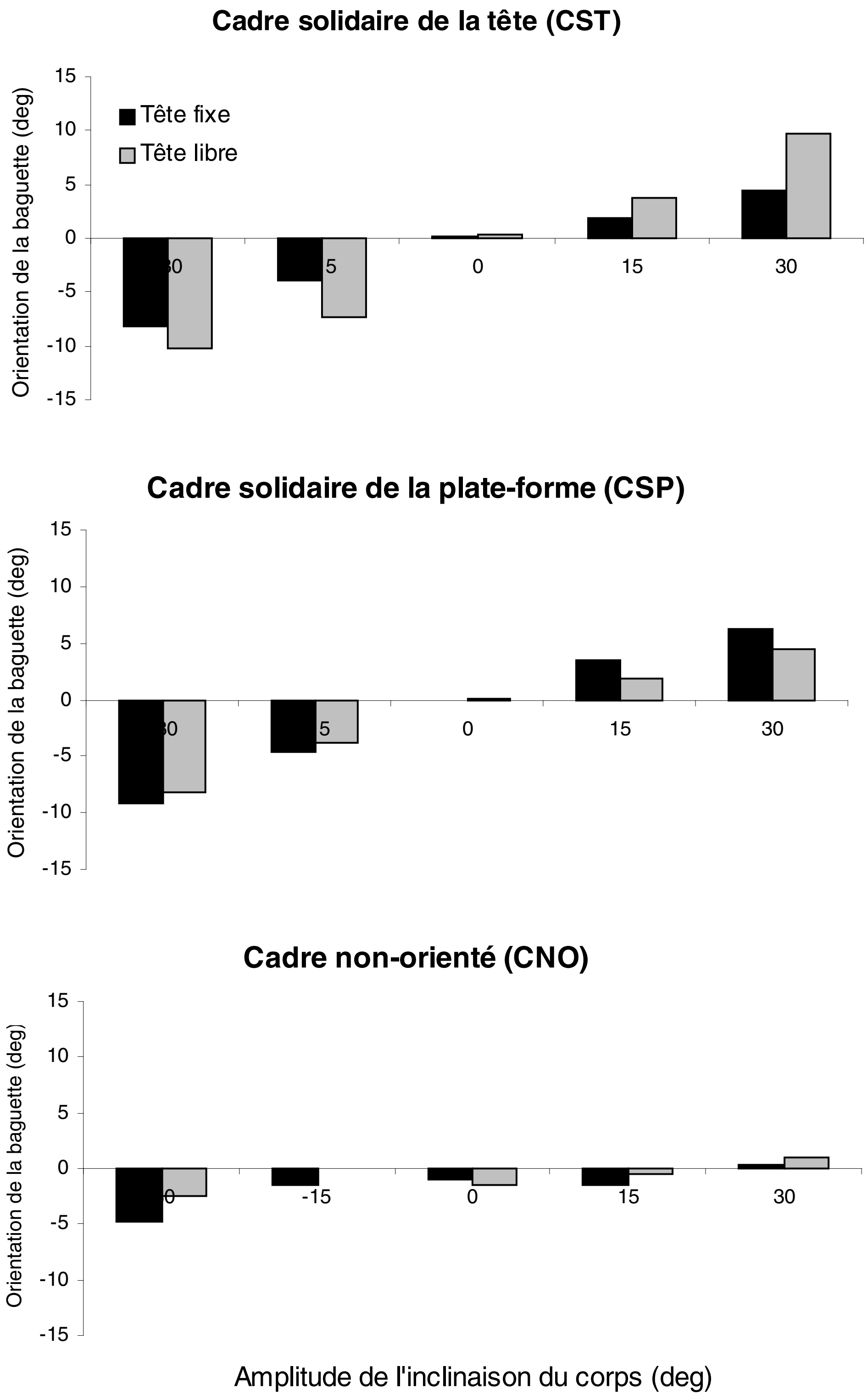

Fig. 5 : Estimation de la verticale en fonction de l'inclinaison du corps, du type de cadre visuel et de la mobilité de la tête. Dans la condition CST, bouger la tête avant l'estimation augmente l'erreur, commise en direction de l'inclinaison du corps et du cadre. Dans la condition CSP, la mobilité de la tête n'a pas d'effet significatif d'un point de vue statistique sur la verticale subjective. On peut cependant observer une légère amélioration de la performance pour toutes les inclinaisons lorsque le mouvement de la tête est permis.

En ce qui concerne la tâche de réorientation de la tête, les erreurs de repositionnement de la tête commises dans le sens de l'inclinaison de la plate-forme se voient attribuer une valeur positive, alors que les erreurs commises dans la direction opposée sont négatives. Les valeurs de référence obtenues sans inclinaison corporelle ont là aussi été retranchées aux données obtenues pendant les inclinaisons. Les erreurs de repositionnement sont à la fois très faibles en moyenne et très variables selon les sujets. Un effet du type de cadre visuel sur les erreurs de repositionnement de la tête peut cependant être mis en évidence en calculant l'erreur moyenne indépendamment de la direction et de l'amplitude de l'inclinaison du corps (Fig. 6) et en comparant ces moyennes à zéro. Dans ce cas, seule l'erreur de repositionnement commise en condition CST est significativement déviée, en l'occurrence dans le sens de l'inclinaison de la plate-forme (p<.05).

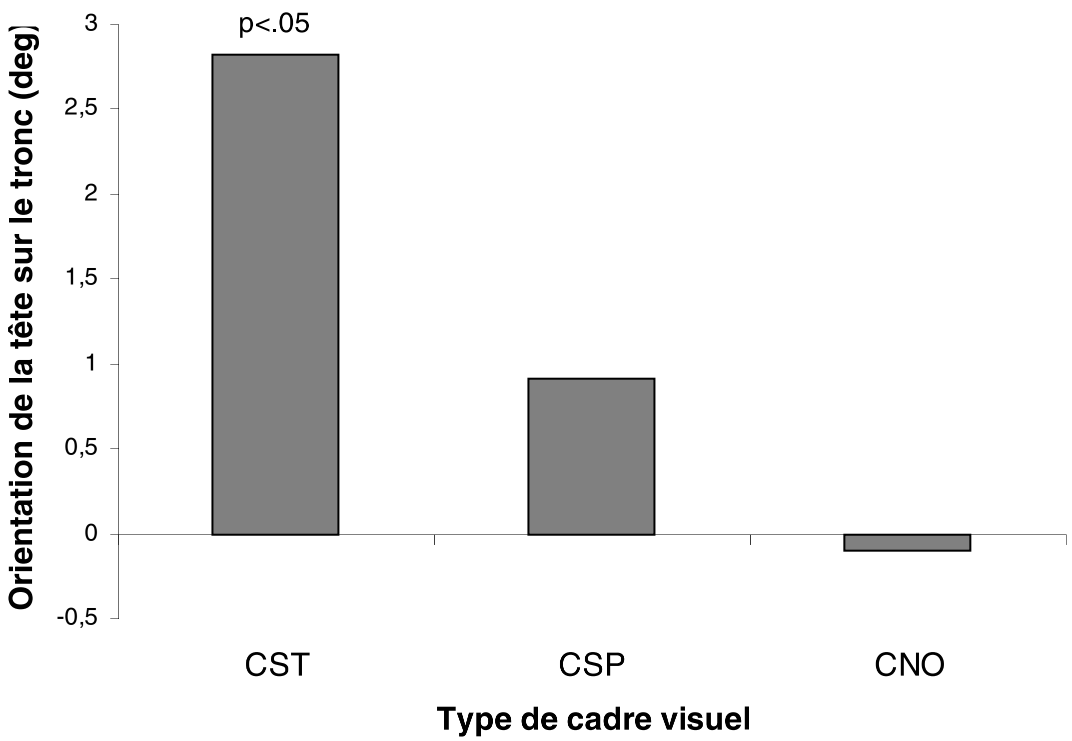

Fig. 6 : Erreur moyenne de repositionnement de la tête en fonction des trois types de cadres visuels étudiés. Une valeur positive représente une erreur dans le sens de l'inclinaison du corps. Seule l'erreur commise avec le cadre solidaire de la tête est significativement différente de zéro.

Les liens entre les erreurs de repositionnement de la tête et les erreurs d'estimation de la verticale peuvent être mis à jour en effectuant une série de corrélations linéaires. Ces corrélations ont consisté à mettre en rapport, d'une part, l'erreur de repositionnement de la tête dans les conditions «tête libre» et d'autre part, la différence entre les erreurs d'estimation de la verticale dans les conditions «tête libre» et celles observées dans les conditions «tête fixe» (Fig. 7). Elles montrent que les deux variables ne sont significativement corrélées que dans les conditions CST (r = 0,64, p<.001). La régression appliquée sur ces données révèle que l'erreur supplémentaire observée en CST-«tête libre» correspond à 70% de l'inclinaison de la tête.

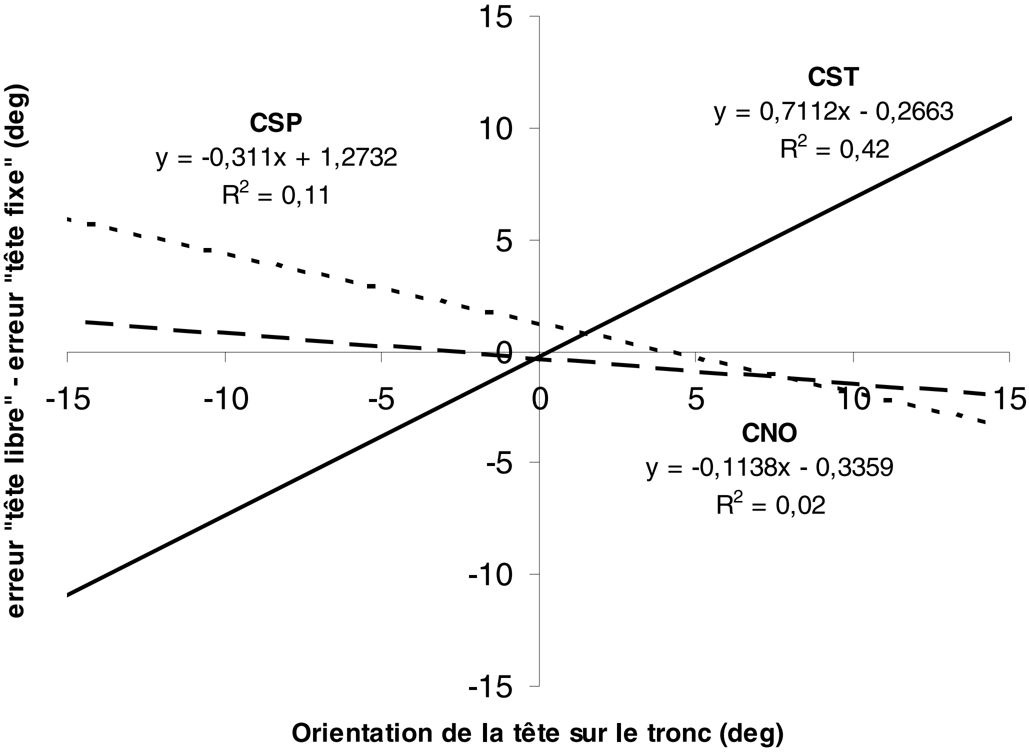

Fig. 7 : Différences d'estimation de la verticale entre les conditions «tête libre» et «tête fixe» en fonction des erreurs de repositionnement de la tête. La corrélation n'est significative que lorsque le cadre visuel est solidaire de la tête.

Discussion

L'expérience 2 visait principalement à comparer les effets de deux types de cadres visuels lors d'inclinaison du corps dans le plan frontal, à la fois sur la perception de la verticale et sur le maintien de la tête dans l'alignement du tronc. L'un des cadres était solidaire de l'orientation de la tête, l'autre s'inclinait avec le corps du sujet, sans toutefois être asservi à la tête. Lorsque la tête est mobile, un cadre visuel céphalocentré génère des erreurs supérieures dans l'estimation de la verticale. Le comportement des sujets dans la tâche de réorientation de la tête diffère également. Les sujets tendent en moyenne à repositionner leur tête dans l'alignement du tronc en présence de références visuelles ancrées dans l'environnement extérieur. Par contraste, la tête est inclinée dans la direction de l'orientation du corps, lorsque le cadre visuel est solidaire de la tête.

Ancrage des références visuelles et réorientation de la tête

La stabilisation de la tête dans l'espace aurait deux fonctions primordiales (Massion, 1994). D'une part, elle intervient comme un élément déterminant dans le contrôle postural et le maintien de l'équilibre et d'autre part, elle permet de fournir aux systèmes perceptifs un référentiel stable. Pour maintenir la tête droite, plusieurs sources d'informations sont utilisées. Premièrement, les indices vestibulaires commandent le réflexe vestibulo-collique, dont l'effet est de redresser la tête dès lors qu'elle n'est plus alignée avec la direction de la gravité. Deuxièmement, les informations proprioceptives issues des muscles du cou participent aux réflexes cervico-colliques qui tend à maintenir la tête dans l'alignement du tronc. On accorde habituellement une importance moindre à la vision sur le maintien de l'orientation de la tête en condition normale, même s'il est reconnu qu'elle peut avoir une influence significative (Guitton et al., 1986).

Lorsque les références visuelles d'orientation ne sont pas alignées sur la verticale, l'influence de la vision peut être clairement mise en évidence par une réorientation de la tête dans la même direction (Guerraz et al., 2001 ; Isableu et al., 1997; Sares et al., résultats non publiés). Sares et al. (résultats non publiés) montrent en particulier que, dans un champ gravito-inertiel modifié, un cadre visuel incliné modifie considérablement le résultat de la compétition entre les réflexes vestibulo-colliques et cervico-colliques. Sur la base de l'ensemble de ces travaux, nous avions fait l'hypothèse qu'un cadre visuel incliné de la même amplitude que le corps améliorerait la performance des sujets dans une tâche consistant à réorienter la tête dans l'alignement du tronc, par rapport à une situation où les informations visuelles étaient solidaires de la tête. Les résultats confirment en partie seulement cette hypothèse. En effet, si la performance moyenne des sujets est meilleure en présence d'informations visuelles ancrées dans l'espace externe, la dispersion des données témoigne d'une assez grande variabilité interindividuelle dans toutes les conditions. Les idiosyncrasies habituellement observées dans les situations expérimentales telles que la nôtre semblent donc se manifester dans la contribution des informations visuelles au choix des «stratégies» de stabilisation de la tête, un phénomène cohérent avec les travaux d'Amblard et al. (2001). En l'absence d'ancrage des informations visuelles dans l'environnement externe au sujet, le comportement de la tête est nettement plus consistant. En effet, les sujets, dans leur majorité, ont tendance à laisser la tête inclinée dans la direction de l'inclinaison du corps. Dans cette condition, les informations visuelles solidaires de la tête sont sans aucune pertinence pour la réalisation de la tâche. En fait, la performance des sujets peut être considérée comme le strict résultat de la modulation volontaire de la compétition entre les réflexes cervico-colliques et vestibulo-colliques. Les premiers vont dans le sens d'une performance adéquate dans la tâche demandée. Les seconds doivent être inhibés pour éviter un redressement de la tête. Visiblement, dans les conditions expérimentales décrites ici, le réflexe vestibulo-collique est sur-compensé.

Ancrage des références visuelles et verticale subjective

Avec un cadre solidaire de la tête, l'estimation de la verticale faite par les sujets après la tâche de réorientation de la tête est significativement plus déviée dans le sens de l'inclinaison du cadre qu'avec un cadre dissocié de la tête. La question se pose alors de savoir quels facteurs peuvent expliquer cette augmentation des erreurs, puisque deux phénomènes coexistent dans cette condition. En effet, le cadre visuel étant solidaire de l'orientation de la tête, les mouvements précédant l'estimation de la verticale ne génèrent aucune variation de l'orientation du cadre dans le référentiel céphalocentré, contrairement à l'autre condition. De plus, si on considère les observations précédentes, il apparaît que les sujets tendent en moyenne à incliner la tête dans la même direction que le corps. Le cadre est donc lui-même incliné par rapport à la gravité d'une amplitude supplémentaire équivalente à celle de la tête.

Les corrélations représentées par la figure 7 ont été réalisées dans le but de déterminer dans quelle proportion cette inclinaison supplémentaire du cadre et de la tête peut expliquer l'augmentation de l'erreur dans l'estimation de la verticale. Alors que les erreurs de repositionnement de la tête ne présentent aucun lien avec les erreurs sur la verticale subjective lorsque le cadre est dissocié de la tête, la corrélation est clairement positive lorsque le cadre est solidaire de la tête. Elle montre que l'augmentation des erreurs observée entre les conditions «tête fixe» et «tête libre» correspond à 70% de l'inclinaison de la tête. Cette proportion est particulièrement élevée au regard des résultats obtenus dans l'expérience 1 où les effets de l'inclinaison de la tête par rapport au corps ont été étudiés. Rappelons que les erreurs observées sur la verticale subjective correspondaient alors à moins de 30% de l'inclinaison de la tête. L'inclinaison supplémentaire du cadre et de la tête dans l'espace peut donc expliquer, au mieux, la moitié de l'erreur supplémentaire observée dans l'expérience 2.

Une autre explication pourrait être avancée. Elle consisterait à dire que l'erreur de réorientation de la tête ne serait pas accessible au système perceptif et viendrait s'ajouter à l'erreur provoquée par l'inclinaison du cadre. En effet, le sujet ayant explicitement pour tâche de réorienter sa tête dans l'alignement du tronc, on peut faire l'hypothèse que l'erreur de repositionnement est la conséquence d'une perception erronée de la tête. L'orientation du cadre céphalocentré étant, par définition, dépendante de la position perçue de la tête, les erreurs perceptives s'ajouteraient. Cependant, la logique de cette éventualité voudrait que l'erreur de repositionnement s'ajoute intégralement à l'erreur observée lorsque la tête est maintenue dans l'alignement du tronc par le dispositif de contention. Ce n'est pas le cas, ce qui nous amène à rejeter cette hypothèse.

Les résultats plaident donc en faveur de l'hypothèse, posée *a priori*, selon laquelle les mouvements de la tête provoquent un conflit informationnel, puisque le cadre visuel change d'orientation dans le référentiel gravitaire tout en restant fixe dans le référentiel céphalocentré. L'augmentation de l'erreur observée ici serait donc une autre démonstration de l'importance cruciale du traitement des informations spatiales relativement à la tête. Cette hypothèse prédisait également une diminution de l'effet cadre lorsque la tête était mobile en face d'un cadre indépendant de la tête. Cette diminution, quoique présente d'un point de vue descriptif pour toutes les orientations du corps, n'est pas significative.

Conclusions

Il a déjà été proposé que la tête sert d'origine à un référentiel important pour les jugements d'orientation (Friedman et Hall, 1996 ; Guerraz et al., 1998b ; Spidalieri et Sgolastra, 1999). Les deux études que nous rapportons ici renforcent cette idée en démontrant les effets d'un cadre visuel céphalocentré sur la perception de la verticalité. Premièrement, lorsqu'un cadre visuel s'incline avec la tête, il donne lieu à des erreurs importantes qui ne peuvent être expliquées par l'addition d'effets visuels et posturaux. Deuxièmement, la vision du cadre lors de ses changements d'orientation dans l'espace ne diminue l'erreur perceptive que lorsque la tête et le cadre sont dissociés. De plus, lorsque le cadre visuel est solidaire de la tête, des erreurs de repositionnement de la tête peuvent survenir et entraîner indirectement des erreurs supplémentaires dans l'estimation de la verticale. Ces résultats suggèrent par conséquent que le traitement de l'information visuelle dans le référentiel céphalocentré est crucial pour le maintien d'une perception constante et adéquate de la direction de la gravité.

Rappelons que les afficheurs de casque sont actuellement développés pour être intégrés dans les appareils militaires car ils présentent l'avantage remarquable de fournir des informations dans le champ visuel du pilote quelle que soit l'orientation de sa tête. A ce titre, des essais sont conduits pour inclure des indicateurs d'attitude dans les afficheurs de casque (Cohen et al., 2001). De plus, Taylor et Kuchar (2000) montrent que ce type d'appareillage peut influencer de façon significative le comportement de la tête du pilote lorsqu'il effectue une manœuvre de rétablissement. Considérés ensemble, ces résultats s'accordent avec les nôtres pour suggérer que si des indicateurs d'attitude, comme une ligne d'horizon, sont entourés d'informations visuelles orientées fixes par rapport à la tête, la perception qu'a le pilote de son orientation peut être significativement altérée. Ceci serait d'autant plus probable lors de vols de nuit durant lesquels des épisodes de désorientation spatiale sont fréquemment rapportés, en raison de l'absence de repères visuels externes. Les informations visuelles orientées n'ont pas forcément besoin d'avoir la forme d'un cadre complet tel que celui utilisé dans les expériences rapportées ici, puisqu'il a été montré qu'un cadre incomplet ou même des contours subjectifs peuvent induire un effet cadre (Antonucci et al., 1995 ; Spinelli et al., 1999; Streibel et al., 1980). Ceci devrait inciter les concepteurs en aéronautique à porter attention aux risques potentiels liés à l'inclusion dans les afficheurs de casque d'informations visuelles dont l'orientation resterait constante par rapport à la tête. Previc (2000) défendait déjà l'idée que l'inclusion d'indicateurs d'attitude asservis à la tête risquait de violer les caractéristiques fondamentales des systèmes nerveux responsables de l'orientation spatiale. Les arguments expérimentaux présentés ici confortent cette idée.

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Assessment of Pilot Performance Using a Moving Horizon (Inside-Out), a Moving Aircraft (Outside-In), and an Arc-Segmented Attitude Reference Display

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Flight symbology offers one of the primary countermeasures that can help prevent and alleviate spatial disorientation. As new helmet-mounted displays (HMDs) are being created, we must develop more effective methods of supplying the pitch and bank information to the pilot. While most flyers have long used the inside-out attitude indicator, or a moving horizon (MH) display, many studies have shown that an outside-in display, or a moving airplane (MP), is more intuitive. However, a recent study at Brooks Air Force Base suggests that a new symbology called the arc-segmented attitude reference display (ASAR) produces even better performance and a faster learning curve than either the MH or MP. If found to be operationally relevant, the ASAR should be considered as a likely candidate for HMD flight symbology.

Students in an introductory flight course at the US Air Force Academy were tested on three different display symbologies, the MH, MP, and the ASAR. The displays were presented on a 17-inch color monitor. The experimental sequence was: (1) practice free flight, daytime scene (2) perturbed flight, nighttime scene, (3) practice unusual attitude recoveries (UARs), nighttime scene and (4) test UARs, nighttime scene. During the UARs, subjects were instructed to first roll the aircraft to level the wings, then recover to straight and level flight as quickly as possible. Six different parameters were analyzed during the study: RMS error in roll and pitch during perturbed flight; time to initial stick input in roll and pitch during the UARs; time to straight and level flight during the UARs; and finally, the number of roll reversal errors during the test UARs.

The subjects had the fastest roll and pitch times to initial stick input when using the ASAR, although this display tended to have slightly poorer subjective ratings. The MP display had a slightly faster time to roll input than the MH, but the pitch inputs were identical. Based on these results, the ASAR display is the most effective at portraying attitude information.

Introduction

Human factors researchers have investigated different forms of aircraft display symbologies since Sperry and Doolittle performed the first instrument-only flight in 1929. These two pioneers of aviation recognized that the attitude indicator (AI) was of paramount importance in maintaining controlled flight in low visibility environments, and continued to improve upon their design. Today the AI is recognized as perhaps the only way to prevent spatial disorientation, which costs the US Air Force alone approximately $80 million per year (1). To help prevent these mishaps, it is necessary to provide the pilot with the most intuitive and effective AI possible.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

Sperry and Doolittle's AI introduced the inside-out display type that is most commonly used today. This AI shows an artificial moving horizon (MH) that lines up with the horizon that the pilot views while looking straight ahead out of the cockpit. When the pilot banks left, the artificial horizon rolls to the right, mimicking the motion of the true horizon. A small aircraft symbol remains stationary in the middle of the display as a reference point. Pitch information is typically portrayed by a pitch ladder. This moving horizon symbology is approved by the Federal Aviation Administration and has been a recognized international standard by most nations.

A second type of AI was developed in the former Soviet Union, and is used by most countries who fly with Russian-built aircraft. The moving airplane (MP), or outside-in display, depicts roll information directly opposite that of the MH AI. In the MP, the horizon actually remains stationary in the display case while a miniature aircraft rolls within the display. When the pilot rolls left, the miniature aircraft rolls to the left accordingly. The MP AI also displays pitch information using a type of pitch ladder; therefore, these displays are a hybrid design rather than a total outside-in concept. Various researchers have reported that the MP tends to be more intuitive than the MH design and that the MP design may cause fewer control-stick input errors (5,6).

While these two displays are the dominant designs used in the civilian and military communities today, many other displays have been proposed throughout the years. One of the most promising is the Arc-Segmented Attitude Reference (ASAR) or Grapefruit display, first introduced in Germany (3,4). The ASAR consists of an arc that changes its position according to the bank angle; this arc length is dependent on the pitch of the plane. The roll information acts similarly to the MH type of symbology – as the aircraft rolls counterclockwise, the arc actually rotates clockwise. As the aircraft pitches upwards, the arc length gets shorter and shorter – if you are flying straight upwards, there is no arc display at all. If you are flying straight towards the ground, the display becomes a full circle.

The current study examines the performance of pilots while using a moving horizon, a moving aircraft, and the ASAR displays. Subjects were two groups of students either before or after they had taken an introductory flight course. Both objective and subjective data were analyzed to determine the benefits of the different AIs.

Methods

The research was performed at the United States Air Force Academy utilizing cadets in their fourth year of studies. Fourteen students were recruited from the MSS 481 course, Airmanship for Military Aviators. Six of the subjects had already completed the class, while the other eight were enrolled when tested. The local Institutional Review Board approved the protocol and informed consent was obtained from all subjects.

Three different display symbologies were utilized in the study. The first mimicked the current symbology used in most aircraft equipped with a head-up display– we will call it the moving horizon or MH display. Figure 1 shows the aircraft during two different attitudes. When nose low, the pitch ladder is shown with angled dashed lines that actually "point" the pilot back up to the artificial horizon.

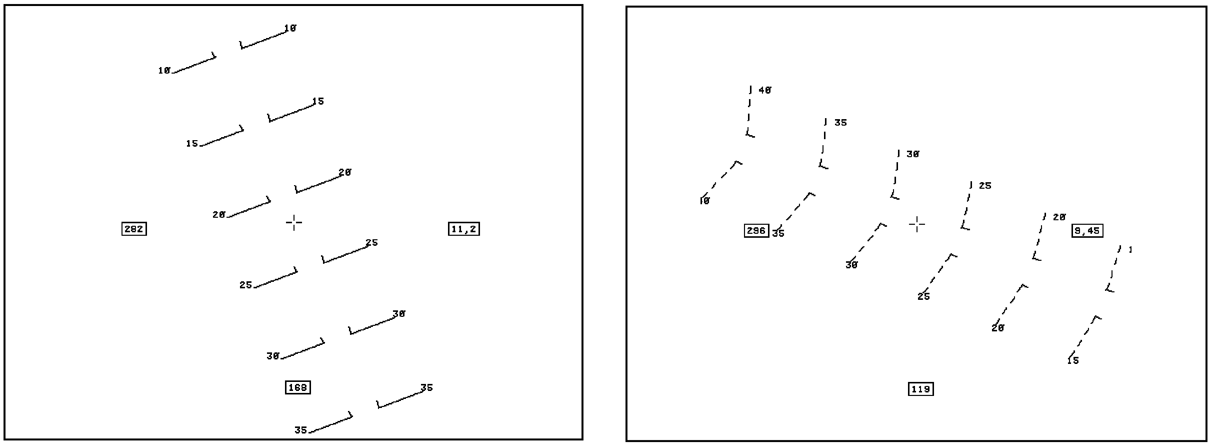

Figure 1. The MH display when flying (a) nose high, inverted, and banked left about 150 degrees and (b) flying nose low, inverted, banked left about 120 degrees.

The second symbology is similar to that used in most Russian made aircraft and will be called the moving aircraft or MP display. As discussed previously, it is actually a hybrid display and utilizes a pitch ladder similar to that used in the MH display above. Figure 2 shows two different attitudes when using the MP symbology. When the aircraft is pitched down so that the horizon line (0 degrees of pitch) is no longer visible, a blinking dashed line appears at the top of the screen to lead the pilot back to straight and level flight.

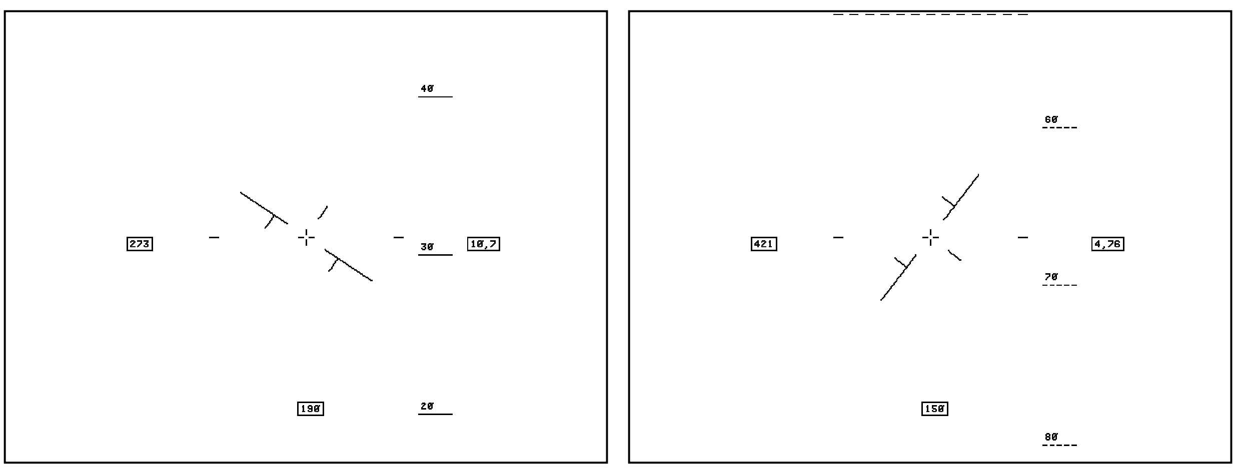

Figure 2. The MP display when flying (a) nose high, banked right about 30 degrees and (b) flying inverted at approximately 120 degrees of right bank.

Finally, the ASAR display is depicted in Figure 3. As discussed earlier, when the aircraft is pitched up the arc length is less than 180 degrees (see Figure 3, left). When the nose is pointed downwards, the arc length increases (see Figure 3, right). The ASAR thus integrates both roll and pitch information into a single display and is an inside-out concept.

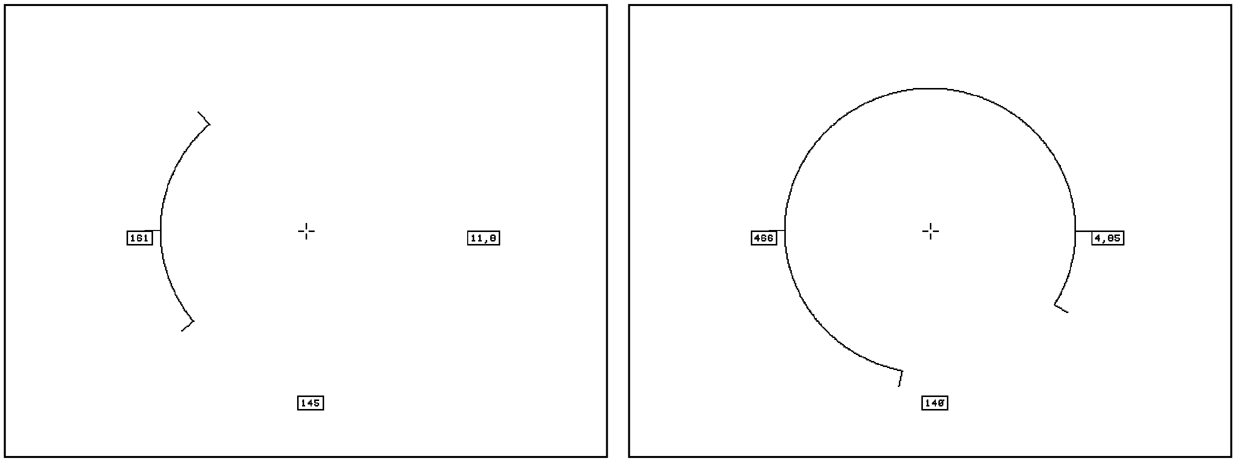

Figure 3. The ASAR display when flying (a) nose high, banked left about 90 degrees and (b) flying inverted at approximately 135 degrees of left bank, nose low.

The test setup is shown in Figure 4. Each subject was seated 30 inches away from a 17-inch computer monitor. A CH Products F-16 Fighter flight stick was used for the control inputs. The Flight Performance Assessment Simulation System (F-PASS) programmed by NTI, Inc (Dayton, OH) was used for the study.

After completing an initial survey, each participant was given a written description of the different display types. They were then allowed up to two full minutes of free-flight, daytime flying on each display. This was followed by a perturbed flight sequence, where each display type was tested for 30 seconds. These tests used a nighttime background scene, as shown in Figures 1-3. The perturbation was created by using five superimposed sine waves with different phase offsets with a gain of 0.5. The algorithm was created randomly, but limits were set for each test sequence to make sure that workload limits were similar for all tests. Roll and pitch root-mean square (RMS) errors were recorded for all perturbed flights.

Figure 4. Experimental test setup.

After the perturbed tests, a sequence of eight practice unusual attitude recoveries (UAR) was presented for each display type. When the subjects were ready, they pressed the flight trigger and an unusual attitude was presented. Subjects were instructed to make a roll input to return the wings to level flight, then try to correct the pitch attitude. The subjects were given a maximum of 30 seconds to return the aircraft to straight and level flight (within 5 degrees of pitch and bank, and for 3 continuous seconds). If they could not perform this task successfully on 5 out of 8 trials with a given display type, they were given a second sequence of eight trials to gain proficiency at the task.

Finally, the test UARs were presented. As in the practice UARs, there were eight different conditions for each display type. There were four roll conditions (±30 and ±120 degrees), and two pitch conditions (± 60 degrees). A total of 24 different test UARs was given to each subject, 8 UARs x 3 displays. Both the display type and the UARs were randomized for every subject. After completion of the tests a subjective survey was given to the participants.

Statistical Analysis

The dependent variables were: time to initial roll input, time to initial pitch input, time to recover to straight and level, number of roll reversal errors, and RMS error during the perturbed flights. The data were analyzed with separate repeated measures analyses of variance. Subjective data were also examined.

Results

The perturbed flight RMS error for roll and pitch, the time to initial stick input for both roll and pitch, and the number of roll reversal errors for each display type are shown in Figure 5. For the perturbed flight, the RMS values in roll were not significantly different for any of the displays (p=0.80). The pitch RMS values were significantly lower for the ASAR display (p= 0.003). Because the time to initial stick input data failed a normality tests, a Friedman repeated measures analysis of variance on ranks was performed on the data. For roll inputs, the ASAR had a significantly faster initial stick input times than the MH display (p = 0.023). The initial pitch inputs tended to be faster for the ASAR than for the other two symbologies, but there were no statistical differences noted (p= 0.146). The time to recover to straight and level was not significantly different for any of the displays (ASAR= 11.8 ± 2.0, MH= 11.2 ± 1.5, MP= 11.2 ± 2.0). There tended to be fewer RREs for the ASAR than the other two displays, but there were no significant differences for these values (p= 0.64). Subjective data are summarized in Table 1.

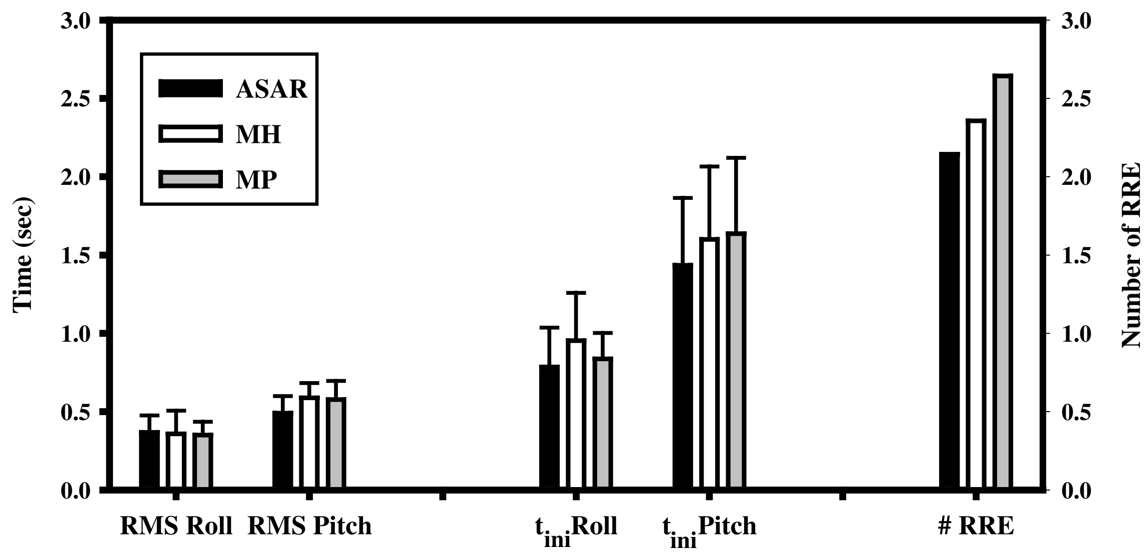

Figure 5. The RMS error in pitch and roll, the time to initial stick input, and the number of roll reversal errors for each display type.

Table I. Mean (s.d.) subjective ratings for the three different display symbologies.

	Was easy to use	**Was confusing to me**	**Was easy to learn**	**I performed well using this display**	**Overall rating**
Scale	***Lickert Scale – 1 strongly disagree, 7 strongly agree***				***1-10***
ASAR	4.57 (1.70)	3.86 (1.51)	4.86 (1.66)	5.07 (1.07)	6.00 (1.84)
MH	5.21 (1.63)	2.36 (1.34)	5.57 (1.60)	5.29 (1.14)	7.93 (1.07)
MP	5.57 (1.40)	2.57 (1.70)	5.93 (1.38)	5.50 (1.45)	7.79 (2.33)

Discussion

The current study is part of a larger research project examining the effects of classroom training on the performance of pilots using three different display symbologies. The MH symbology used in most aircraft follows the familiar inside-out approach championed by Sperry and Doolittle. As has been shown in many other studies, some doubt that this symbology is the most intuitive type of display for the AI. With proper pilot training, however, it has proven to be a successful and a reliable display. It is interesting to note that the MH display resulted in the longest time to initial roll input – the horizon can be somewhat non-intuitive when first presented. When the aircraft is rolled left, the artificial horizon is actually banked to the right, causing a control-symbology movement mismatch.

The MP display is similar to those used in Russian built aircraft. The roll display is an outside-in design, while pitch information is provided by a pitch ladder (similar to the MH design). Several studies have shown that this may be more intuitive than an inside-out display. The initial roll input was somewhat faster than the MH display, and can be explained by the fact that the aircraft mimics the stick input. Since both the MH and MP designs portray pitch information using a pitch ladder, it is not surprising that the time to initial pitch input was similar for the two displays.

The ASAR performed well in the study, having the fastest stick inputs in both roll and pitch. It also provided the smallest RMS error in pitch, which suggests that the changing arc length is an efficient means in which to supply pitch information. It is also interesting to note that the subjective ratings for the ASAR tended to be the poorest of the three, even though the students had their highest performances using the ASAR. This may be explained by the fact that most people are not familiar with this concept.

The results can be compared to a recent study that examined the use of the ASAR on a helmet-mounted display (HMD). In that study, the ASAR had the fastest roll input times (pitch information was not recorded), the fastest recovery, the fewest roll reversal errors, and was the most preferred. The subjects in the HMD study were all experienced pilots (2). The times for initial stick input were quite a bit faster for the cadets than for these pilots – this may be indicative of the students trying to complete the task as rapidly as possible.

Conclusions

The ASAR continues to prove itself, whether with experienced or novice pilots. Continued studies with cadets with varying levels of flying experience and expertise can help determine the most efficient display symbologies to use in future aircraft. These studies can eventually be performed using HMDs in simulators and even in flight at the US Air Force Academy.

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A Tool to Maintain Spatial Orientation and Situation Awareness for Operators of Manned and Unmanned Aerial Vehicles and other Military Motion Platforms

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The Naval Aerospace Medical Research Laboratory has developed a Tactile Situation Awareness System (TSAS) that intuitively provides spatial orientation, navigation and threat/targeting information to operators of various military platforms. The TSAS consists of tactile stimulators (tactors) on the torso and limbs of the body that relay processed information from a variety of sensors to the operator.

Since 1992, the advantages of TSAS have been demonstrated in several applications including helicopters, fixed-wing, Unmanned Aerial Vehicles (UAVs), High-Altitude High-Opening (HAHO) parachuting, undersea, and land (1-5). Before any piece of hardware becomes part of the military inventory, the user community conducts operational test and evaluation (OPTEVEVAL) and Operational Utility Evaluations (OUE) to identify strengths, weaknesses, and suitability in a wide variety of operational conditions. These tests also serve to develop concepts of operation.

In the first section of this paper, we will present some of the data collected during an Operational Assessment (OA) of TSAS conducted by the 18th Flight Test of the USAF at Hurlburt Field. In the second portion, we address some of the strengths and weaknesses of TSAS technologies and the improvements made over the past decade.

PART ONE. 18TH FLIGHT TEST DATA

BACKGROUND

TSAS Concept

The TSAS uses the sense of touch to provide spatial orientation and situational awareness (SA) information to pilots and crew members. The system reads data from current aircraft systems, processes it, and then relays designated information using miniature tactile stimulators called tactors. Two types of tactors are currently available: pneumatic and electromagnetic. The pneumatic tactors are comprised of plastic bodies with latex bladders. Air is pulsed through the tactor and felt as a distinct tapping when placed against the body. The electromagnetic tactors have a magnet and electrical coil and, when energized, produce a unique tapping sensation that "feels" different than the pneumatic tactors. The pneumatic tactors are located in a cooling vest; the electromagnetic tactors are located under the thighs and on top of the shoulders.

Hardware

The NP-3 system is comprised of five main subelements: a processor unit, two pneumatic valve sets, an interface control unit, a compressed air source, and two vests. The TSAS processor is a PC-104 computer system in a custom enclosure. The processor interprets the aircraft's 1553 data bus information and generates signals for the pneumatic valves and the electromagnetic tactors. For this test, the processor unit was mounted on an instrumentation rack. The valve sets regulate compressed airflow to the tactors. For

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the flight, one valve set was mounted on the right-hand seat. For the simulator sessions, valve sets were mounted on the pilot, copilot, and flight engineer seats. The interface unit is a commercial off-the-shelf (COTS) Panasonic ruggedized computer used to control various TSAS mode functions. While the final configuration for an air source in aircraft has not been determined, for this test, a COTS SCUBA tank was used. Both the interface unit and the compressed air source were mounted on an instrumentation rack. The vests are YF-22 cooling vests modified with 24 pneumatic tactors and 4 electromagnetic tactors each. Figures 1 and 2 show an early prototype of the TSAS vest. The pneumatic tactor-line umbilical, electromagnetic umbilical, and ventilation air hose terminate in quick-disconnect connectors.

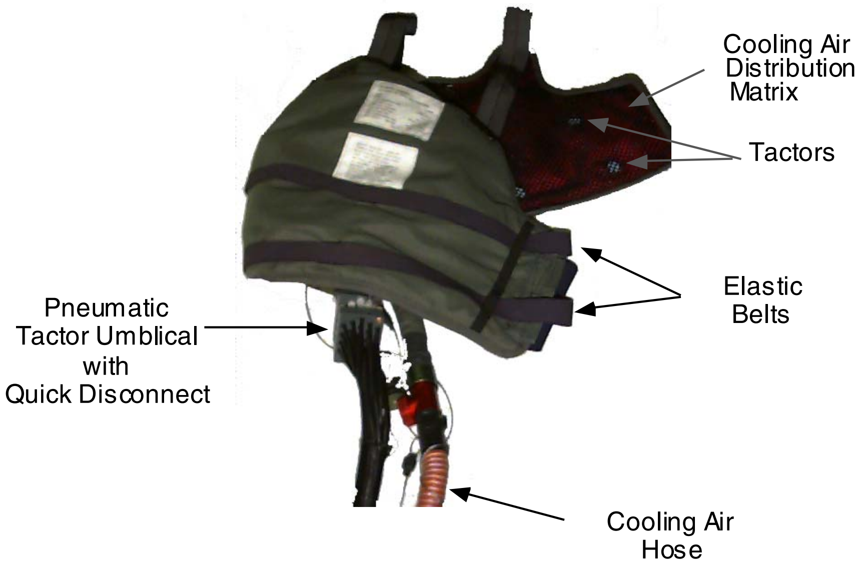

Figure 1. TSAS Vest

Figure 2. Wearing the TSAS Vest

The TSAS is designed to enhance SA by providing cues to the pilots. Current applications include hover cues and terrain following/terrain avoidance (TF/TA) climb, dive, and steering cues. The crew can follow the TSAS directions or refer back to the aircraft instruments. The system can be set up to provide hover cues automatically below a set airspeed. In this configuration, the system provides indications of lateral, longitudinal, and vertical deviations during a hover. The hover configuration frees the crew to operate other aircraft systems rather than visually monitoring aircraft hover cues. During TF/TA operations, the TSAS echoes the climb/dive command cues the crews receive on current instruments. The TF/TA configuration allows the crews to focus on other tasks. Additional applications include lateral steering, flight director guidance, and threat warning indications. While the system was demonstrated to work independently of existing aircraft visual instruments, it is not intended to entirely replace visual stimuli.

METHOD

The TSAS prototype was tested using the CV-22 simulator and flight testing in an MH-53M helicopter. Testing in the simulator compared flight performance with and without TSAS. Time constraints caused the test team to eliminate vertical cues from this portion of the test. Therefore, to maintain consistency in results, vertical cues are not presented in this report. Lateral and longitudinal velocity errors were combined to produce a single velocity error. Most suitability issues were addressed by discussions with aircrews on integrating the TSAS with aircraft systems and missions. Due to aircraft availability and the bulkiness of the new body armor, TSAS was not tested in flight with body armor. The TSAS was tested for 25 simulation hours on 8-9 Jun, 8-10 Aug, and 12-13 Oct 2000 at the CV-22 simulator at Bell Helicopter Plant 1, Hurst, Texas. MH-53M flight tests were limited to three missions, and were flown at Hurlburt Field and Eglin Range on 16, 17, and 22 Nov 2000 for 6.9 flight hours.

Simulator Testing

TSAS was integrated into the CV-22 simulator at Bell Helicopter Plant. Aircrews used TSAS in the fixed-point mode and general hover modes. For fixed-point mode, the tactile cues keyed the pilots to fly the aircraft within a box around a specific geo-referenced point based on aircraft position. To evaluate this mode, the crew flew a simulated fast rope insertion to a specific point on the ground. For the general hover mode, TSAS provided hover cues based solely on aircraft velocities to establish a good hover regardless of location. In hover mode, the crew duplicated the maneuvers found in Table 1 during day and night visual meteorological conditions. The TSAS processor unit, which monitors the aircraft navigation system, recorded flight information for post-mission analysis. A direct comparison was made between errors with and without TSAS. The crew was also surveyed to evaluate and comment on the effectiveness/ compatibility of using TSAS during hover operations with good hover cues (day) and limited hover cues (night). The survey used a scale from 1 (very ineffective) to 4 (very effective). The test team measured the percentage of positive responses (a score of 3 or 4). When time permitted, aircrews also evaluated other applications of TSAS such as TF climb/dive commands, lateral steering cues, and flight director guidance for instrument approaches. Initial simulator testing was not successful in capturing quantitative data. Subsequent simulator tests included very little time on controlled hover operations like those in Table 1, focusing instead on more realistic missions. During testing, aircrew members quickly adapted to the lateral and longitudinal cues from the vest, but they took additional time to learn the vertical cues. Also, only the general hover mode was analyzed due to difficulties in data retrieval. Unlike the flight data, which compared "TSAS Off, Hover Displays On" to "TSAS On, Hover Displays Off," the simulator data are presented as "TSAS On" versus "TSAS Off" for both visual situations (On and Off). The difference is due to the lack of additional motion and extra visual cues in the real world that are not available in the simulator.

Table 1. Standard Hover Maneuvers

Task	Maneuver	Time[a]	AGL[b] (ft)
1	Stationary in ground effect (IGE) hover	120 s	10
2	Left 180° hovering turn	Hover 20s after	10
3	Longitudinal hover for 100 ft	Hover 20s after	10
4	Rearward hover for 100 ft	Hover 20s after	10
5	Left sideward hover for 50 ft	Hover 20s after	10
6	Right sideward hover for 50 ft	Hover 20s after	10
7	Stationary out-of-ground effect (OGE) hover	120 s	100
8	Longitudinal hover for 100 ft	Hover 20s after	100
9	Rearward hover for 100 ft	Hover 20s after	100
10	Right 180° hovering turn	Hover 20s after	100
11	Left sideward hover for 50 ft	Hover 20s after	100
12	Right sideward hover for 50 ft	Hover 20s after	100
13	Stationary hover	20 s	10
14	Land		

[a] Amount of time to maintain stable hover after completion of maneuver
[b] Above Ground Level

Flight Test

During the flight test, pilot and copilot duplicated the hover maneuvers from the CV-22 simulator portion of the test (Table 1). Due to safety considerations, all tasks were performed at 100 ft above ground level (AGL) rather than those listed in the Table. The simulated shipboard takeoff was not tested because of time constraints and aircraft availability. The first and second flights were flown during daylight over water 5 miles off shore to minimize outside visual cues. The third flight occurred over land at night using night vision goggles. The test environment had minimal to no outside visual cues, especially at night. The TSAS processor unit, which acquires 1553 bus data, recorded flight information for post-mission analysis. A direct comparison was made between errors with and without the TSAS. The crew also completed surveys to evaluate and comment on the effectiveness/compatibility of using TSAS during hover operations. The survey uses a scale from 1 (very ineffective) to 4 (very effective). The test team measured the percentage of positive responses (a score of 3 or 4). All quantitative data were reviewed after each mission; however, only the data from Table 1, tasks 1 and 7 were used for performance measures. Test conditions involved "TSAS Off, Hover Displays On," which is the current method of flight, and "TSAS On, Hover Displays Off." The latter method tests a worst-case scenario for TSAS in which TSAS and outside visual cues were the only input the pilot had to maintain a stable hover. The "displays" refer to the hover cues available on visual instruments. The lateral and longitudinal velocity errors were averaged to produce a combined velocity error.

RESULTS

The USAF 18th Flight Test (FLTS) was tasked to perform an Operational Assessment to answer a critical operational issue: Does TSAS show the potential to improve aircrew performance?

Critical Operational Issue

The answer to the question, "Does the Tactile Situational Awareness System show the potential to improve aircrew performance?" is YES. Three out of three measures of effectiveness (MOEs) met criteria. TSAS was evaluated during three different sessions at the CV-22 simulator and on three flights on an MH-53M. In both cases, analysis of hover errors (measured in velocity) improved with TSAS usage. Additionally, aircrew ratings indicated TSAS was effective in reducing aircrew workload and increasing SA. Aircrew members who used TSAS agreed it was effective in the applications tested.

Measures of Effectiveness 1

Aircrew Hover Performance in Flight and Perceived SA. Criteria: Both performance and SA must improve with TSAS usage. MET CRITERIA. One out of four measures of performance (MOPs) met criteria, while the remaining three MOPs had no significantly measurable evaluation criteria. Quantitative data recorded during flight showed hover performance, measured as drift velocity, improved significantly with TSAS usage. Aircrew members agreed unanimously that TSAS was effective, and it reduced workload and improved SA.

Vertical, Lateral, and Longitudinal Errors During Hover Maneuvers Measured in Distance and Velocity. Criteria: Hover performance (holding a stable hover) improves with TSAS usage. MET CRITERIA. The average hover performance improved with TSAS usage as shown in Table 2. The fourth pilot in Table 2 did not show a significant difference with TSAS on or off during the initial hover checks. The test team did observe that pilot 4 became fatigued after an hour of hovering. Thus, pilot 4's performance diminished without TSAS but improved with TSAS. This result warrants further investigation into the benefits of TSAS during long missions. Overall, pilots using TSAS were able to spend more time "outside the cockpit," thus improving their overall SA. The quantitative data presented in Table 2 are for the 2-min stabilized hover from Table 1, tasks 1 and 7. Figure 3 shows a summary of the average velocity errors for each pilot and an overall average.

Table 2. Flight Test Velocity Errors

Pilot	TSAS On, Displays Off			TSAS Off, Displays On			Significantly Different?
	Mean	Stdev	N	Mean	Stdev	n	
Overall[a]	2.3109	1.2352	657	2.4762	1.5014	679	Yes
Pilot 1	2.0861	1.1293	140	2.5213	1.2917	140	Yes
Pilot 2	1.9509	1.0517	279		no data		N/A
Pilot 3	2.7314	1.2728	255	2.9512	1.7557	274	Yes
Pilot 4	2.0218	1.1380	262	1.9613	1.1052	265	No

[a] Does not include pilot 2

Aircrew Ratings of TSAS Effectiveness. Criteria: None. Sample size does not allow for statistically significant results. Five aircrew members evaluated TSAS effectiveness over the course of three flights. All rated the system as 4 (very effective). Several pilots commented that the cues were accurate, timely, and easy to interpret.

Aircrew Rating of TSAS' Ability to Reduce Workload. Criteria: None. Sample size does not allow for statistically significant results. Five aircrew members rated the ability of TSAS to reduce workload as 4 (very effective). One pilot wrote, "the system definitely helped to reduce workload. The TSAS allowed me to divert my attention to other tasks." Another added, "[TSAS] reduced my workload tremendously!! TSAS enabled me to decrease my cockpit scan to altitude and heading control only. Felt like second nature to rely on drift corrections from TSAS."

Aircrew Rating of TSAS' Ability to Improve SA. Criteria: None. Sample size does not allow for statistically significant results. Five pilots evaluated TSAS' effectiveness over the course of three flights. All rated the system as 4 (very effective) for improving SA. One pilot commented that he "would get TSAS inputs before [he] could recognize drift visually."

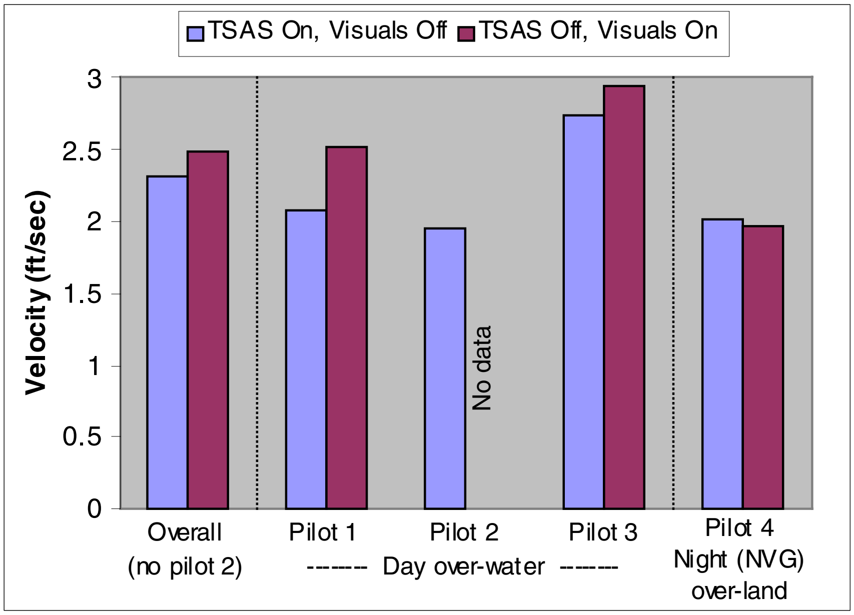

Figure 3. Flight Test Velocity Errors

Note: The average value does not include pilot 2 because all data could not be collected for that pilot due to an aircraft malfunction**.**

Table 3. Simulator Velocity Errors – Hover Displays On

Pilot	**TSAS On**			**TSAS Off**			**Significantly Different?**
	Mean	**Stdev**	**n**	**Mean**	**Stdev**	**n**	
IGE (10 ft)							
Overall*	0.7824	0.4367	8004	0.9650	0.6298	8004	Yes
Pilot 1	0.8536	0.4837	2001	1.5387	0.6546	2001	Yes
Pilot 2	0.6980	0.2569	2001	0.9213	0.4332	2001	Yes
Pilot 3	0.6386	0.3357	2001	0.7680	0.6156	2001	Yes
Pilot 4	0.9393	0.5414	2001	0.6320	0.3335	2001	Yes
OGE (100 ft)							
Overall	1.0620	0.6825	14007	1.2386	0.9687	14007	Yes
Pilot 1	1.1861	0.7923	2001	1.4428	0.9436	2001	Yes
Pilot 2	0.9795	0.4419	2001	1.3642	1.0852	2001	Yes
Pilot 3	0.8200	0.3308	2001	0.8201	0.4042	2001	No
Pilot 4	1.0412	0.6067	2001	1.3228	0.7604	2001	Yes
Pilot 5	0.8127	0.3100	2001	0.8203	0.3560	2001	No
Pilot 6	0.8998	0.4355	2001	0.7904	0.4342	2001	Yes
Pilot 7	1.6950	1.0513	2001	2.1099	1.4391	2001	Yes

Note: Table 3 lists the average, standard deviation (Stdev), and sample size of velocity errors (n) for both test conditions.

Measures of Effectiveness 2

Aircrew Hover Performance in the CV-22 Simulator. Criteria: Hover performance must improve with TSAS usage. MET CRITERIA. Two out of two MOPs met criteria. Quantitative data recorded during simulator sessions suggest hover performance measured as drift velocity improved significantly with TSAS usage. Additionally, qualitative data based on survey responses showed aircrew members agreed unanimously that TSAS was effective for improving hover performance.

Vertical, Lateral, and Longitudinal Errors During Hover Maneuvers Measured in Distance and Velocity. Criteria: Hover performance (holding a stable hover) improves with TSAS usage. MET CRITERIA. Overall, hover performance improved in all four test conditions. Tables 2 and 3 list the detailed values producing the figures. Figures 4 and 5 show a summary of the average velocity errors for each pilot (right side) and an overall average (left side) for both test conditions. The data show TSAS improved hover performance in seven-of-nine scenarios with "Hover Displays On" (Table 3 and Figure 4) and four-of-four scenarios with "Hover Displays Off" (Table 4 and Figure 5).

Table 4. Simulator Velocity Errors – Hover Displays Off

Pilot Performance	TSAS On			TSAS Off			Significantly
	Mean	Stdev	n	Mean	Stdev	n	Different?
IGE (10 ft)							
Overall	1.1256	0.6950	6003	1.5220	0.9767	6003	Yes
Pilot 1	1.5623	0.7686	2001	1.5485	0.8268	2001	No
Pilot 2	1.1668	0.5683	2001	2.2061	1.0441	2001	Yes
Pilot 3	0.6478	0.3390	2001	0.8112	0.3382	2001	Yes
OGE (100 ft)							
Overall	2.4035	1.3363	6003	2.6162	1.4274	6003	Yes
Pilot 1	3.0624	1.2424	2001	3.3093	1.8058	2001	Yes
Pilot 2	2.7573	1.3784	2001	2.7876	1.0638	2001	No
Pilot 3	1.3909	0.5740	2001	1.7517	0.6811	2001	Yes

Note: Each table lists the average, Stdev, and number of velocity errors (n) for both test conditions.

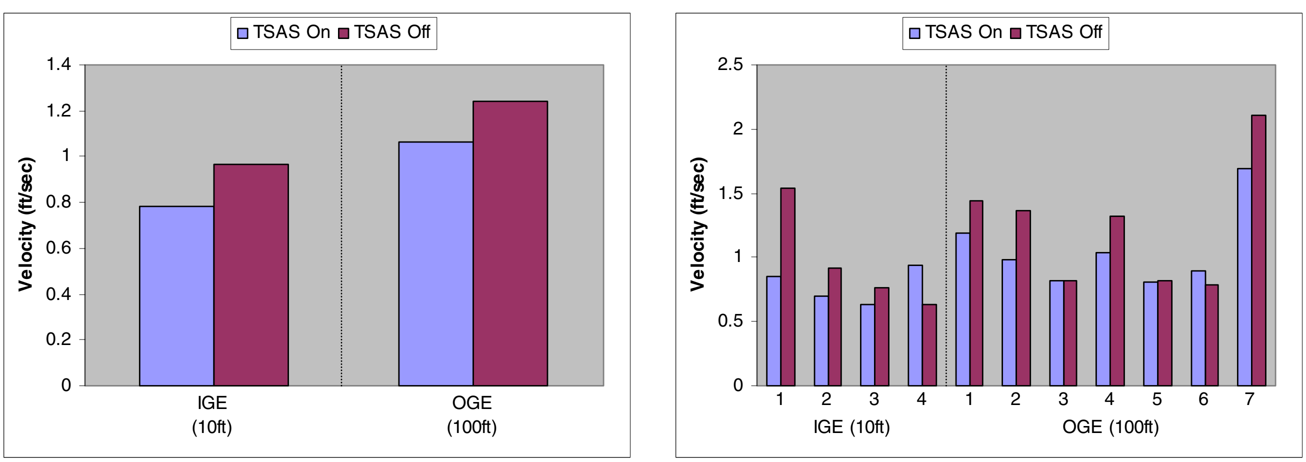

Figure 4. Simulator Velocity Errors – Hover Displays On

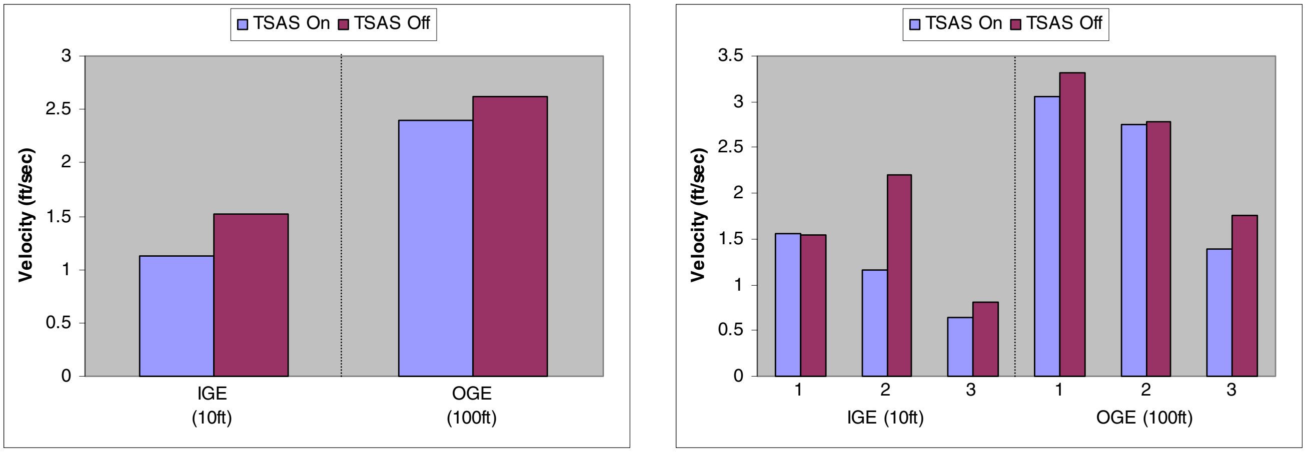

Figure 5. Simulator Velocity Errors – Hover Displays Off

Aircrew Ratings of TSAS' Effectiveness. Criteria: Eighty percent responses must be rated 3 (effective) or better. MET CRITERIA. A total of nine pilots and three flight engineers evaluated TSAS' effectiveness over the course of three sessions at the CV-22 simulator (some of the pilots attended more than one session). All rated the system as 3 (effective). Several pilots commented that the cues were accurate, timely, and easy to interpret. Pilot 5 stated, "even though the inputs were the opposite of what was expected, a comfort level was obtained within 15 minutes." Despite the positive ratings, the majority of pilots said they did not like the shoulder cues, which indicated the aircraft was above a set altitude. Vertical cueing consisted of electromagnetic tactors placed on the pilot's shoulders for down vertical cueing and under the thighs for up vertical cueing. If the aircraft were higher or lower than set altitudes, the tactors would activate telling the pilot to move the aircraft up or down. No crewmembers liked the down vertical cueing, but most liked the up vertical cueing. Further TSAS testing was recommended using vertical cueing to see if there is added value for using this feature

Measures of Effectiveness 3

Aircrew Ratings of TSAS' Potential for Use in Other Aspects of the CV-22 Mission. MET CRITERIA. Three out of four MOPs met criteria. During the second two simulator sessions, TSAS was used to provide cues for TF climb/dive commands, tactical lateral steering guidance, flight director guidance for instrument approaches, and threat information. With the exception of tactical lateral steering guidance, aircrew members considered all TSAS modes effective. They particularly liked the threat information.

Aircrew Rating of TSAS' Effectiveness for Cueing TF Climb/Dive Commands. Criteria: Eighty percent of the responses must be rated 3 (effective) or better. MET CRITERIA. Cueing for TF climb/dive commands was only evaluated in the last two simulator sessions. There were seven pilots and three flight engineers, with two of the pilots attending both sessions for a total of 12 responses. Only one pilot rated the system 2 (ineffective). All others (92%) rated the TF climb/dive commands as 3 (effective) or better. The one pilot who disagreed rated the system as effective during the first simulator session but did not like the dive cue; however, the pilot did state, "TF climb cue is very effective." In the second session, this pilot said the TSAS cues were a triple redundant input already provided by visual and audio cues. The majority of other aircrew members had similar comments about climb versus dive, but they seemed to like the cues. The flight engineers in particular liked the system because it "allows heads down CDU/EICAS (Control Display Unit/Engine Indication and Crew Alert System) work." They recommended that further TSAS testing with threat awareness information be conducted due to the high potential for timely crew threat information. Another flight test recommendation was for each aircrew position to have independent TSAS controls and settings for sensitivity/mode/frequency. Each aircrew position should be configured when the pilots are planning flight/mission profiles. These data should be down loaded to the mission computer and controlled through the CDU for further changes as the mission progresses.

Aircrew Rating of TSAS Effectiveness for Cueing Lateral Steering Guidance Back to Course. Criteria: Eighty percent of the responses must be rated 3 (effective) or better. DID NOT MEET CRITERIA. Cueing for lateral steering guidance was evaluated in the last two simulator sessions. There were 7 pilots and 3 flight engineers, with 2 pilots attending both sessions for a total of 12 surveys, but only 7 evaluated lateral steering guidance. Of the seven surveys, five (71%) rated the lateral steering guidance as 3 (effective). One of the two surveys stating the guidance was ineffective came from pilot 1 who said it was effective in the first simulator session. Even those who said the cues were effective commented they were not needed. Further TSAS testing was recommended for cueing lateral steering guidance back to course to see if there is added value for this feature.

Aircrew Rating of TSAS' Effectiveness for Cueing Flight Director Guidance (ILS/VOR). Criteria: Eighty percent of the responses must be rated 3 (effective) or better. MET CRITERIA. Cueing for flight director guidance was only evaluated in the last two simulator sessions. There were 7 pilots and 3 flight engineers, with 2 pilots attending both sessions for a total of 12 surveys, but only 7 evaluated flight director guidance. Only one pilot rated the system as 2 (ineffective). All others (86%) rated the flight director guidance (ILS/VOR) commands as 3 (effective) or better. Aircrew members liked the cueing for flight director guidance and rated it an "excellent tool for ILS approach" and "excellent for IMC approaches." The flight test recommended TSAS cueing be used for all aircrew during all phases of hover/flight so the crew will not be confused between cues and command guidance. Cueing is defined as aircraft trend information (tap on left indicates aircraft is moving left), command guidance tells the aircrew where to move the flight control (tap on left, move flight control to the left).

Aircrew Rating Of TSAS' Potential for Providing Other 1553 Data Bus Information via the Sense of Touch. Criteria: Eighty percent of the responses must be rated 3 (effective) or better. MET CRITERIA. A total of nine pilots and three flight engineers evaluated TSAS effectiveness over the course of three sessions at the CV-22 simulator (some pilots attended more than one session). All pilots rated the system as 3 (effective) or better for providing 1553 data bus information. By far, the most common suggestion was to include threat information with TSAS. This was tested during the second simulator session with great success. The flight test recommended further exploration of the data on the 1553 data bus that can be used by the TSAS to enhance aircrew SA.

ADDITIONAL FINDINGS AND RECOMMENDATIONS

TSAS has the potential to provide noncockpit crewmembers on the MH-53M with threat awareness information and aircraft position. This could be provided with electromagnetic tactors receiving a signal from a wireless data link from the processor unit. We recommend using TSAS for noncockpit crewmembers on the MH-53M for threat awareness information and aircraft position.

TSAS has the potential to provide air-conditioned and heated air for aircrew comfort. Our recommendation is that air-conditioned and heated air be used in the TSAS vest for pilot comfort and to reduce fatigue over long missions.

TSAS has the potential to assist Special Tactics Forces during air and ground navigation. We recommend a modified self-contained version of TSAS for night operations during high-altitude low-opening/high-altitude high-opening (HALO/HAHO) under canopy navigation and ground navigation for Special Tactics Forces.

Unmanned aerial vehicle (UAV) operators maintain SA by referencing monitor displays on a ground control station or an individual control unit. Relevant platform telemetry data and a forward look-ahead view from the platform are depicted while a second display shows payload perspective. When in manual control of the platform, the ability to sense platform movements or irregularities in flight is visual, making approaches and landings challenging. A TSAS interoperability test with UAVs could be conducted to gather human factors for the necessary sensory inputs during crucial phases of flight information with future UAV systems. We believe that future testing should be conducted on TSAS for interoperability with UAV operators and related systems.

TACTICAL CONSIDERATIONS

The TSAS can be programmed to relay any information on the 1553 data bus to the crew via the sense of touch. New tactics may be needed to take advantage of the TSAS. One example is changing the instrument scan pattern for the aircrew. Because TSAS provides the same information as the instruments, the crew can spend more time looking outside the aircraft or performing other duties and only referring back to instruments when TSAS indicates the aircraft has deviated from the intended position or course. Potential application for TSAS includes steering cues, TF/TA, land/water rescue, missile warning/tracking, target tracking, low-altitude warning, and ground collision avoidance system.

CONCLUSIONS AND RECOMMENDATIONS FROM 18th FLIGHT TEST

TSAS improves aircrew SA, reduces aircrew workload, and demonstrates potential suitability for the AFSOC mission. The prototype TSAS, in its conception phase, is not operationally suitable for the AFSOC mission; however, with further refinement and continued testing, it can become an effective aircrew aid during critical phases of flight.

Specific Enhancing Characteristics

Some of the TSAS' potential applications were explored in the CV-22 simulator during tactical mission profiles. One of the most promising uses for TSAS involves missile warning/tracking cues combined with TF climb/dive inputs. The missile warning inputs came from the missile-warning receiver. The TSAS vest provided excellent threat SA to the crew through the use of variable frequency directional inputs. Search radar would induce a very low frequency directional tactile input to the crew while changes to higher threat lethality states resulted in higher frequency inputs. A missile launch indication would give the crew a very high frequency "buzz," indicating immediate action required. Combined with the vertical cueing from the TF radar, missile warning cues gave the crew excellent SA on the threat situation as well as excellent terrain awareness.

Specific Deficiencies

None

SPECIFIC RECOMMENDATIONS

Recommend further TSAS testing using vertical cueing to see if there is added value for using this feature.

Recommend further TSAS testing with threat awareness information due to the high potential for timely crew threat information.

Recommend each aircrew position have independent TSAS controls and settings for sensitivity/mode/frequency. Each aircrew position should be configured when the pilots are planning flight/mission profiles. These data should be downloaded to the mission computer and controlled through the CDU for further changes as the mission progresses

Recommend further TSAS testing for cueing lateral steering guidance back to course to see if this feature adds value.

Recommend TSAS cueing be used for all aircrew during all phases of hover/flight so the crew will not be confused between cues and command guidance. Cueing is defined as aircraft trend information (tap on left indicates aircraft is moving left), command guidance tells the aircrew where to move the flight control (tap on left, move flight control to the left).

Recommend further exploration of the data on the 1553 data bus that can be used by the TSAS to enhance aircrew SA.

PART TWO. TSAS TECHNOLOGY & APPLICATIONS UPDATE

The TSAS has been tested in a wide variety of applications and environments since 1991. Each successive version resulted in further refinements to produce a system that is now ready for use by military and civilian communities. The advances have been made in five areas: Tactile Stimulators (Tactors), Power Source(s), Tactor Locator System(s) (TLS), Software Control Systems, and Devices to Test Integration.

The presentation of tactile information has varied from simple, point-source single tactors, to complex collections of tactors to provide two or more types of information simultaneously or to provide "flow" information over large portions of the torso and limbs. An example of problems encountered during testing with an early prototype that has resulted in improvements is that of flow sensations. The presentation of flow requires several tactors activated in specific patterns. We first used flow to provide the sensations of whole-body rotation or moving linearly (horizontally or vertically) at various velocities when the 8 x 5 matrix in a torso suit became available in 1991. When the rings were activated sequentially, this suit could provide sensations of "up" or "down" movement. The value of this sensation was later tested on the H-60 motion-based simulator at the US Army Aeromedical Research Laboratory in Ft Rucker Alabama. Although the test pilots approved the vertical flow sensation as an effective means to nonvisually maintain altitude, it was not possible to present other information at the same time and thus not used in-flight. This testing however, revealed several deficiencies in the state of the art, as it existed in 1995, including the need for several things: tactor locator systems that could provide a larger array of improved tactors, held at the optimal pressure against the skin; a control system that had minimal delays to permit real time user interaction with motion based platforms or simulators; and perhaps most importantly, tactors that could be controlled accurately in the frequency, amplitude and waveform dimensions and which were instrumented to provide feedback of the stimulus parameters delivered to the skin. Although flow patterns were impossible to demonstrate, meaningful tactile research was futile without full awareness and control of the tactile stimulus. The advances made over the past 10 years have now provided the current TSAS laboratory system with the required controls and feedback.

TACTILE STIMULATORS

The first tactors used for TSAS tests were COTS products such as Tactaids, small vibrators and miniature speakers. The primary weakness of these early tactors was an inadequate stimulus amplitude to produce a robust sensation in the noisy, high-vibration environment found in aircraft.

In 1995, the US Navy sponsored--under a combination of the Advanced Technology Demonstration program and the Small Business Innovative Research (SBIR) program--several companies to advance the development of a wide variety of novel tactors. Tactor development suffered from an inability to compare the effectiveness of one tactor with another due to a lack of standard psychophysical measures for touch sensation. Initially, one commercially available tactor was picked as a "standard" against which to compare other tactors until the Navy established an in-house psychophysics laboratory to evaluate new tactors as they were developed.

The ideal tactor can be controlled in frequency, amplitude, and waveform over the biological useful ranges. It should be small, rugged, waterproof, and lightweight and provide indentation and tangential "stroke" stimuli. It is instrumented to provide feedback, has no electromagnetic or acoustic signature, requires little power, and is inexpensive. Unfortunately, it does not yet exist. The tactors used for a given application must be selected from what is currently available, or a customized new design is required.

An SBIR-developed waterproof electromechanical tactor that we used for underwater applications was found to provide excellent stimuli for diving applications. Unfortunately, for obvious reasons, the Explosive Ordinance Demolition (EOD) community could not use a tactor with appreciable acoustic or magnetic signatures. This tactor in the nonwaterproof form has, however, found application in the aviation community.

The pneumatic tactor developed under a request from the Joint Strike Fighter Program has proven to be very rugged, relatively cheap, and lightweight. It has a small acoustic but no magnetic signature, produces a wide range of frequency and amplitude stimuli, and is the best all-round tactor for aviation applications currently available. This tactor has been used by NAMRL for the past 6 years. A weakness in this pneumatic tactor for laboratory applications is related to the use of air, a compressible gas, which results in a lack of fidelity of transmission of the stimulus parameters delivered at the pump compared to the stimulus reaching the skin. Many of these difficulties are resolved with our in-house hydraulic tactors.

Another solution to the problem of defining the stimulus delivered to the skin is the use of instrumented tactors or placing a pressure sensor on the skin close to the tactor which records the transmitted energy the tactor is providing. The cost and complexity of instrumented tactors make large arrays very expensive.

Considerable room exists to improve tactors, and the field is wide open for a tactor that will provide a well-controlled, tangential "stroking" stimulus.

Power Sources

Power sources were designed for both laboratory investigation systems as well as smaller, more robust systems for mobile platforms. The development of power sources for tactors was complicated by the need to accommodate more than one type of tactor simultaneously. For example the current lab system drives large combinations of 96 pneumatic, hydraulic, and electrical tactors simultaneously.

An in-house developed motor is used to drive the laboratory pneumatic and hydraulic systems. The mobile pneumatic system, such as the unit described in Part One, used compressed air bottles as the power source and a series of valves to control individual tactors.

Software Controls

The NAMRL TSAS laboratory systems are designed to provide maximal control of the tactile stimulus for scientists to develop algorithms used in the optimization of the stimulus pattern for a given application. Each of the 96 tactors is under separate frequency, amplitude, and waveform control. It is important for closed-loop control of dynamic platforms that the combination of software controls and power sources has minimal delay between sensor information and the time the stimulus providing the sensor information is relayed to the skin. In visual systems, 50-ms delays are annoying and detract from performance. The NAMRL TSAS system was designed to have no more than 1-ms delay in delivery of electromechanical stimuli and 2 ms for pneumatic and hydraulic stimuli. These delays are so minimal as to be lost in the "noise" of the biological system.

The Graphical User Interface (GUI) is important especially when there are large numbers of tactors, each of which can be controlled in frequency, amplitude, and waveform. The GUI includes a visual display of the body and limbs with each tactor represented and user-selected groupings of tactors to facilitate use of the TSAS lab system by researchers not fluent in C programming.

Tactor Locator System

Perhaps the most difficult technical challenge for the TSAS engineering team has been developing a garment that will maintain a large variety of tactors with different pressure requirements for optimal performance against the skin with the correct pressure(s) while the user is in motion. The initial prototypes used thin diving wet suits or other snug-fitting sport garments made of Lycra type materials with additional straps to maintain tactors in the appropriate location with the optimal loading characteristics. Flight-capable systems, even for testing of prototypes, had to be constructed of fire-retardant stretch Nomex to meet safety requirements.

An early breakthrough was the F-22 prototype cooling garment. This snug-fitting heating/cooling vest proved to be the ideal flight-approved garment that, in addition to providing the appropriate pressures to a restricted area of the torso, also serendipitously offered climate control of the skin as well as lumbar support for pilots. The primary drawback of the F-22 vest is that it cannot be modified to apply tactors on the upper torso and/or proximal limb. Full-torso coverage is necessary to provide the most intuitive awareness of targeting and complete pitch-and-roll coverage for fixed-wing applications including remote control of unmanned vehicles operating in three dimensions.

Through a combination of in-house development and SBIRs, we now have a variety of prototype suits with full torso and proximal limb coverage, in which it is possible to selectively control the pressures the tactors exert against the skin. NAMRL has developed a suit evaluation box (SEB) to measure the variables of concern in prototype suits. The variables include humidity and temperature in more than one area and pressure in 12 locations.

Another technical problem to be addressed for military applications is the need for TSAS compatibility with the current suits that provide chemical and biological warfare (CBW) protection. Integration of electromechanical tactors with CBW suits does not pose a problem, but the complexities of interfaces with pneumatic and hydraulic tactors will require further engineering development.

Test Devices

In early stages of TSAS development in 1989, we recognized that a collection of man-rated acceleration devices would be required to optimally integrate the tactile display system with other sensory information systems including visual displays and 3-D sound displays. Visual and aural perceptual illusions of target location occur when humans are exposed to significant linear or angular acceleration as occur on current aviation platforms. Research on visual, tactile, or 3-D sound systems can be conducted virtually anywhere, but to investigate the effects of sensory interaction in acceleration environments requires man-rated devices capable of providing linear and or angular acceleration and the appropriate visual/tactile/aural cues. To that end, the Navy Bureau of Medicine has built the Visual Vestibular Sphere Device (VVSD) (Figure 6).

The VVSD is a 12-foot diameter sphere capable of rotating up to 30 RPM about any axis between the earth vertical and horizontal. The occupant can be stationary or rotated independently about an axis collinear with the sphere in the same or opposite direction. The VVSD is being used to investigate the interaction of tactile stimuli with visual and aural displays in a dynamic angular motion environment. Other NAMRL devices with less compelling visual displays are available when it is necessary to conduct sensory integration tests requiring linear or combined linear and angular acceleration (6).

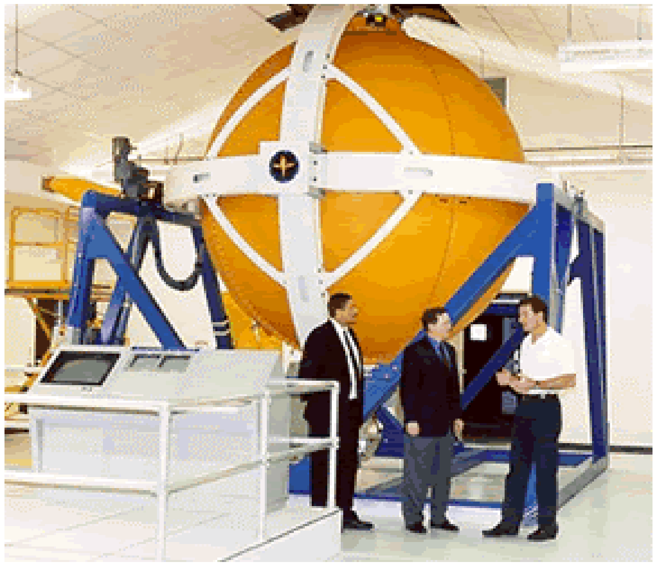

Figure 6. Visual Vestibular Sphere Device (VVSD)

APPLICATONS

The original military requirements pushing the development of TSAS were the loss of SA and disorientation problems experienced most dramatically in aerospace and diving communities and secondarily in ground forces. Spatial disorientation occurs in the aviation environment, in large part, due to false information provided by the inner ear and skin-muscle-joint systems as to the direction "down." In space, there is no "down" nor sense of down provided by the proprioceptive systems. On the ground, the information is generally accurate except in the case of sensory compromised individuals, especially the aged. TSAS can serve as a prosthesis in all these conditions.

From a theoretical perspective, the most difficult of the above sensory conditions for which to provide a solution is the aviation environment. In this condition, not only is the sensory information provided by vestibular and somatosensory systems frequently wrong, it is also concordant between these systems, and hence the orientation illusions are most compelling when visual clues are lost due to distraction or diversion of visual attention of the operator from visual orientation cues. In space, there is simply an absence of information, and on the ground the sensory information is usually merely degraded. For these reasons, validation of TSAS as a balance prosthesis in the aviation environment where the sensory condition is most challenged, argues well for its value to counter the relatively easy sensory deficit condition in space and the trivial condition of clinical terrestrial imbalance.

We have used TSAS successfully as a balance prosthesis in the aviation and terrestrial environments. Multiple test flights in a variety of platforms by all the services have demonstrated TSAS effectiveness. On the ground, NAMRL researchers have effectively used TSAS to provide subjects with an intuitive prosthesis to maintain balance during laboratory-induced acute vestibular defects. Although the aviation prosthesis was the most challenging from a sensory perspective, it was the easiest from a technical point of view because reliable, accurate sensors already exist (i.e., aircraft attitude instruments), and the platform (plane or helicopter) is relatively stable. Alternatively, the theoretical trivial terrestrial sensory condition poses a most difficult technical problem, namely designing a sensor and algorithm that will consistently provide fall prediction with very few errors in a highly unstable platform (human). The penalty for design error would be a fall that in the elderly frequently leads to a broken hip and subsequent demise.

CONCLUSIONS

1. TSAS is an effective prosthesis for sensory compromised individuals whether they are pilots, astronauts or patients suffering balance disorders.

2. As shown by operational assessment, TSAS is an effective tool for improving situation awareness and reducing workload in the high tempo military environment.

3. TSAS should be incorporated into helicopter platforms to reduce brownout and whiteout mishaps.

4. Improvements to TSAS should be focused on (a) the development of new tactors to include stroking tangential tactile stimulators and (b) garment technologies that will provide consistent tactor contact over the full torso and proximal limbs.

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Enhanced Situation Awareness in Sea, Air and Land Environments

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Summary

United States (US) military Special Forces teams currently use 2D visual displays for navigation information in the air, in water, and on the ground. These current displays demand the user's visual attention, which can compromise mission effectiveness, and using visual displays in low light visibility environments can cause fatigue, degrade performance, and compromise a clandestine situation. If navigation equipment that is dependent on visual displays were integrated with a tactile display, the need to use vision for navigation could be minimized. The operator could be more effective if his eyes were used to survey the surroundings rather than continuously monitor a visual display.

The Tactile Situation Awareness System for Special Forces (TSAS-SF) was developed to investigate the potential of tactile displays for Special Forces operations. The TSAS-SF will upgrade present 2D visual navigation displays and will provide non-visual, non-audible navigation information to Special Forces personnel by interfacing navigation information with a tactile display. This new capability will provide 2D direction cues to the skin, which will free the user's visual senses for higher priority tasks (e.g. contact identification and classification). Preliminary testing in a High Altitude, High Opening (HAHO) parachute environment and a ground environment, and earlier testing in an underwater environment (McTrusty, Walters, 1997, Rupert, McTrusty, Peak, 1999), have demonstrated that navigation can be performed faster with tactile cues than visual cues, and superior navigational accuracy can be achieved with less mental fatigue on the operator. These results suggest that a tactile display that provides 'eyes free' and 'hands free' air and ground navigation information may provide the opportunity to devote more time to other instruments and tasks when operating in high workload conditions. These effects can increase mission effectiveness. The preliminary results from the air and ground navigation tests justify continued testing and evaluation to extend the capabilities of the tactile display, for use as an operational device for navigation in sea, air and land environments.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

Introduction

United States (US) military Special Forces teams use a variety of insertion methods to advance to their area of operations. One of the methods of insertion involves the use of highly maneuverable square parachutes for High Altitude High Opening (HAHO) parachute operations. HAHO operations involve jumping from an aircraft, opening the parachute at a high altitude, and navigating over a long distance towards a designated target-landing zone. It is common for the HAHO operator to be aloft for 25 minutes, and travel distances of 30 miles. After landing, Special Forces teams must navigate on the ground to the area of operations. Currently, all navigation and altitude information in the air, and navigation information on the ground are provided by 2D visual displays. These displays demand the user's visual attention compromising mission effectiveness. Moreover, using visual displays in low light visual environments can cause fatigue, degrade performance, and compromise clandestine situation.

If current navigation displays were integrated with a tactile display, the need to use vision for navigation could be minimized. The operator could be more efficient if his eyes were used to survey his surroundings rather than continuously monitor a visual display. Preliminary testing for the Very Shallow Water Mine Countermeasure (VSWMCM) detachment (McTrusty, Walters, 1997) has shown that underwater navigation can be performed faster with tactile cues than visual cues, and superior navigational accuracy can be achieved with far less mental fatigue on the operator. It is postulated that a tactile navigation display will have similar benefits for a HAHO and ground operations and allow for 'eyes free' and 'hands free' navigation.

The Naval Aerospace Medical Research Laboratory (NAMRL) developed the aviation-based Tactile Situational Awareness System (TSAS) to reduce aircraft mishaps caused by Spatial Disorientation (SD) and subsequent loss of Situation Awareness (SA). TSAS is an advanced display that exploits the under-utilized sensory channel of touch to provide spatial orientation and SA information to aircraft operators (McGrath, 2000). Results have shown that tactile displays are effective in reducing SD and loss of SA problems (McGrath, 2000; Griffin, Pera, Cabrera, Moore 2001). Further research has also suggested that the application of tactile cues may be expanded beyond spatial orientation issues, to areas such as navigation, communication, warning, and training (Walters, 1998). The TSAS concept is shown in Figure 1. The TSAS system accepts data from various sensors and displays this information via miniature tactile stimulators called *tactors* integrated into flight gear.

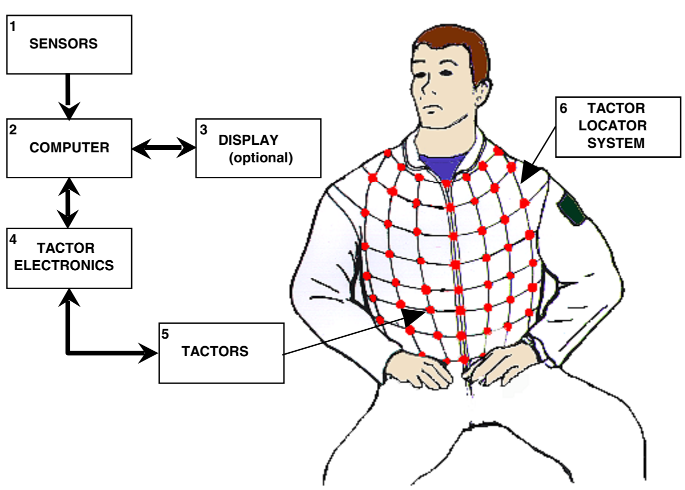

Figure 1: TSAS Concept

The tactile display has been shown to increase SA and provide the opportunity to devote more time to other instruments and systems when operating in task saturated conditions (Griffin, et. al., 2001; McGrath, 2000). The TSAS system reduces user workload and thus has the potential to increase mission effectiveness. TSAS is capable of providing a wide variety of information, including: attitude, altitude, navigation, threat location, and target location.

To investigate the potential of tactile displays for Special Forces navigation, NAMRL researchers developed a tactile display based on the aviation-based TSAS shown in Figure 1. This system, designated TSAS-SF will upgrade present navigation 2D visual displays and will provide non-visual, non-audible navigation information to Special Forces personnel by interfacing navigation information with a tactile display. This new capability will provide 2D direction cues to the skin, which will free the user's eyes for higher priority tasks, such as contact identification and classification. This new capability provides silent navigation cues to the skin, yielding a more clandestine system. This system has the potential to reduce operator workload and improve performance, especially in extreme tactical environmental conditions (low/no visibility, urban operations).

Method

System Description

The prototype TSAS-SF system (Figure 2) is comprised of a commercial off the shelf (COTS) portable global positioning system (GPS) manufactured by Garmin, a COTS PC-104 central processing unit (CPU) (Real Time Devices CMC6686GX233HR-128), a custom 5 channel tactor driver board and five electromechanical tactors (Engineering Acoustics, Inc.). The CPU and tactor drive electronics are housed in a water resistant sealed housing, with data, tactor and operator switch interfaces. The electronics housing is contained in a pouch with straps for positioning on the operator's leg. The GPS is mounted in a pouch with chest strap loops for visual access during testing. For operational use, the system could interface with existing military GPS units or COTS sensors. The system requires only timely digital data from position or direction sensors.

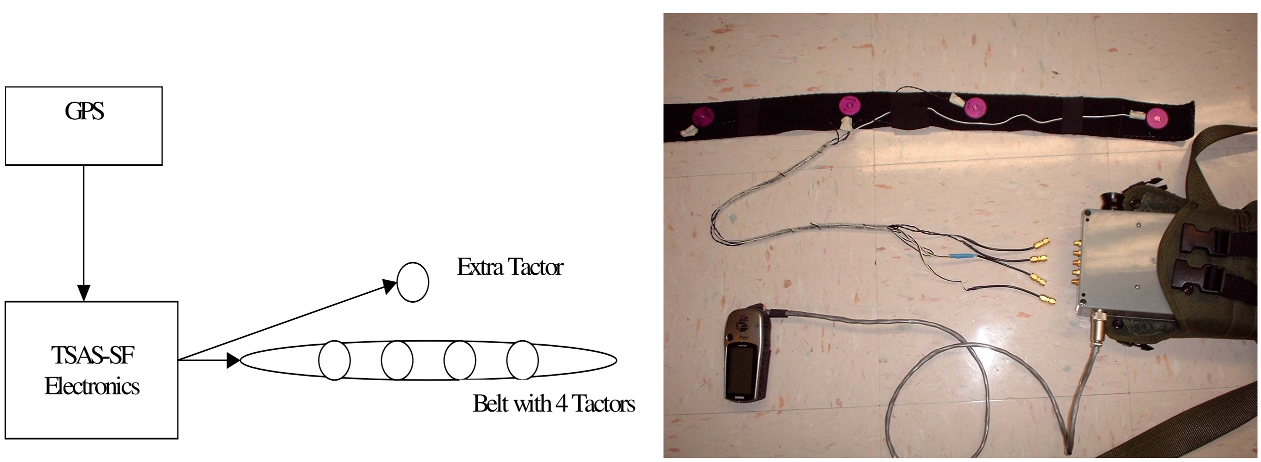

Figure 2. TSAS–SF block diagram (left) and components (right).

The four belt tactors are worn around the operator's waist. The fifth tactor is located near the left collarbone to indicate error conditions and increasing distance from target. To enhance the GPS performance, an external antenna is attached to the top of the operator's helmet after the parachute is opened.

Air Navigation Set-Up

For the air navigation tests, the tactor meanings were mapped as shown in table 1. The tactile symbology used was for the operator to steer away from the stimulus. For example, if the left tactor activated, the operator steered right. If the target overshoot tactor activated, the glideslope was made steeper.

Table 1: Air navigation tactor definitions.

Tactor	Position	Meaning
1	Left	Left of path (steer right)
2	Right	Right of path (steer left)
3	Front	Above glideslope angle (overshoot waypoint)
4	Rear	Below glideslope angle (undershoot waypoint)
5	Extra	Distance to waypoint increasing (moving away or backwards)

In the aircraft prior to the jump, the GPS is pre-programmed with a destination waypoint. After exiting the aircraft and opening the parachute, the operator enables the TSAS-SF system via the power switch. The controller software waits for the initial position data from the GPS. Using the pre-programmed destination waypoint and the initial position data, the great circle course and the distance to the waypoint are computed. Subsequent position data from the GPS are used to calculate cross track distance, distance to go, and glideslope error from the initial position. The glideslope error is recalculated every ten seconds. The left or right tactors fire when the cross track error is greater than the allowed cross track error (tested at fifty feet). The front or rear tactors are fired when the glideslope error angle is outside the glideslope error window (tested at five degrees). The extra tactor fires if the distance to the destination waypoint increases instead of decreases. All tactors fire if no data is received from the GPS within three seconds.

The test plan called for several equipment integration jumps, emphasizing operator safety. The jumps were made from a civilian Cessna 182 light aircraft, using commercial sport parachuting rental equipment. Once familiarized with the equipment and cabling, data collection jumps followed. Nine jumps were made, four equipment jumps followed by five data collection jumps. Distances from destination ranged from two and a half (2.5) nautical miles to six nautical miles, and all jumps were from an altitude of eleven thousand feet above sea level.

Ground Navigation Set-Up

Special Forces teams have ground navigation requirements that are currently met using visual GPS and compass displays. To evaluate tactile displays for ground navigation performance, test subjects walked a predetermined course and completed an additional visual search task. The TSAS-SF for ground navigation only used three of the five tactors. The tactor mappings are shown in Table 2.

Table 2. Ground navigation tactor definitions.

Tactor	Position	Meaning
1	Left	bear left to waypoint heading
2	Right	bear right to waypoint heading
3	Front	stop – waypoint within arrival circle radius

During ground operations, the system was configured to indicate direction to a waypoint. The left and right tactors indicated direction to steer using a “steer towards” stimulus algorithm. The tactors also varied in their pulse rates, pulsing more quickly as heading error increased. Table 3 shows the meanings of the various pulse rates. Once the waypoint was reached, the front tactor pulsed for 3 seconds, indicating waypoint arrival.

Table 3. Ground navigation tactor pulse meanings.

Difference between current heading And heading back to search path	Tactor fire rate in Pulses per second
0 to 15 degrees	0
15 to 30 degrees	1
30 to 90 degrees	2
Greater than 90 degrees	4

Results

Air Navigation Tests

For test purposes, a simple direct flight path was chosen. Winds aloft were averaged to reduce cross track errors caused by winds and a straight-line single leg path to the target was flown. Variations from the intended path were taken only to ensure a safe landing area. On all of the jumps, the intended landing area was reached. It was noted that if the operator faced away from the target, the symbology was reversed. This would need to be corrected in actual mission conditions.

The maximum cross track error was twenty feet during the first three data collection jumps. This resulted in too many corrections, and was increased to fifty feet. The glideslope guidance (five degree window) worked well, but was sometimes ignored, due to concerns for operator safety. Representative data for the cross track error and glideslope error data are shown in Figures 3 and 4, respectively. Forested terrain between the aircraft exit point and target inhibited better testing of the glideslope input.

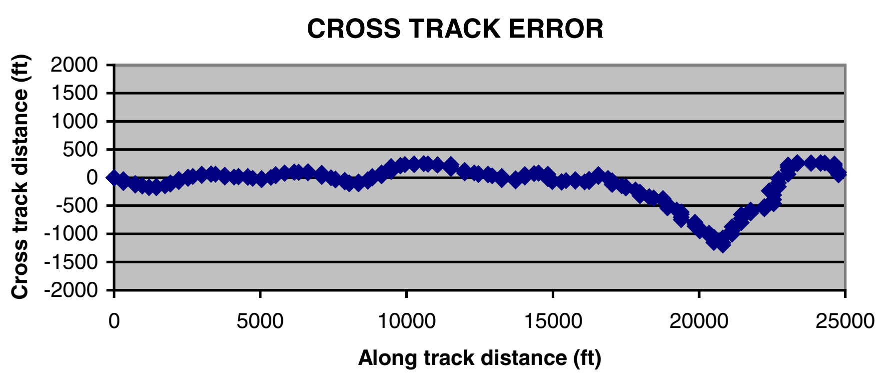

Figure 3. Air navigation cross track error.

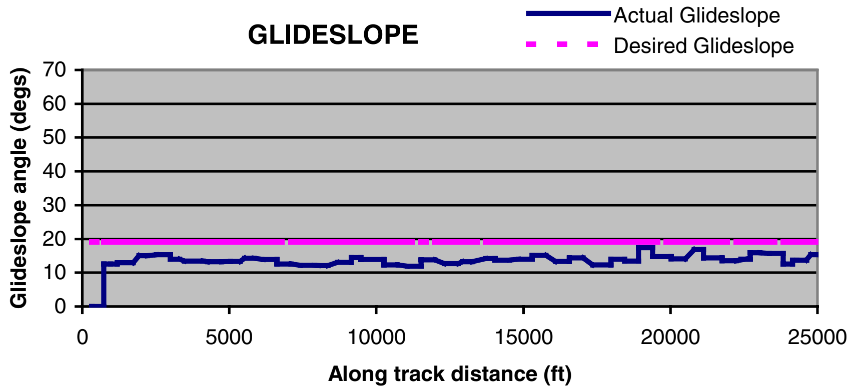

Figure 4: Air navigation glideslope angle.

Ground Navigation Tests

During ground tests, a five-minute, sixteen tenths of a statue mile, three-leg course was mapped. Each subject first navigated the course using the TSAS-SF tactile display, and second using only the visual display on the GPS. For this preliminary investigation, no attempt was made to minimize order effects. For additional visual tasking, a number of small objects, ten green and ten black were placed along the route. A count of the number of objects of each color observed on each run was taken. Table 4 summarizes the results.

Table 4. Ground navigation test results.

Subject	**Time TSAS On (mins)**	**Time TSAS Off (mins)**	**Object counts with TSAS On**	**Object counts with TSAS Off**
1	4.0	5.0	4 green + 6 black = 10	4 green + 1 black = 5
2	4.0	4.0	4 green + 3 black = 7	3 green + 2 black = 5
3	5.0	7.0	5 green + 7 black = 12	4 green + 3 black = 7
4	5.0	4.0	5 green + 3 black = 8	3 green + 1 black = 4
Average	4.5	5.0	9.25	5.25

Preliminary data showed that the number of objects correctly identified is higher with TSAS-SF rather than with only a visual display. This result suggests that the use of the tactile navigation allows the subject more “heads up” time, improving search capability. Figure 5 shows a representative plot of ground track for TSAS-SF on and TSAS-SF off. The ground track data and the object count data in Table 4 suggest that using TSAS-SF improves navigation performance.

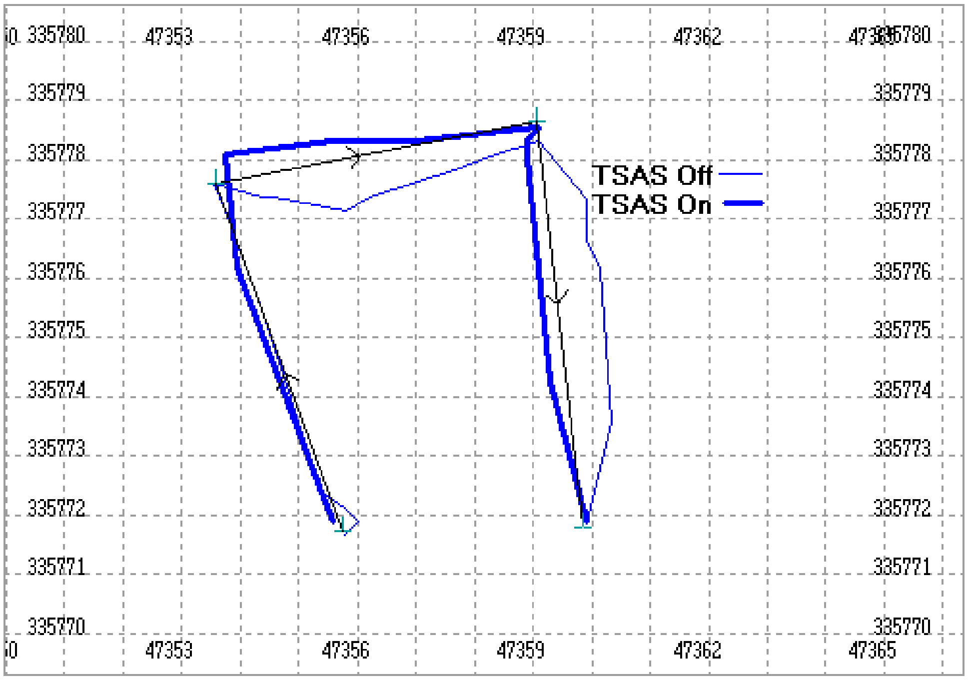

Figure 5. Example of ground navigation using either visual or tactile cues.

Each subject completed a questionnaire and the tabulated results are shown in Table 5.

Table 5: Ground navigation test questions.

QUESTION	**Yes**	**No**
1. Were you confident in your ability to navigate with the VISUAL display?	3	1
2. Were you confident in your ability to navigate with the TACTILE display?	4	0
3. Do you feel you were properly trained to perform these tests?	4	0
4. Did the VISUAL equipment operate properly?	4	0
5. Did the TACTILE equipment operate properly?	3	1
6. Was the tactile stimulation strong enough?	4	0
7. Do you think you can perform a visual search using the navigation system with the VISUAL display?	3	1
8. Do you think you can perform a visual search using the navigation with the TACTILE display?	3	1
	Visual	**Tactile**
9. Which search method do you feel is easier to use?	0	4
10. Which navigation method do you feel produced the best search?	1	3
11. Which search method do you prefer?	0	4
	Yes	**No**
12. Do you feel tactile navigation would increase your search capability?	4	0
13. Were the tactile signals ambiguous or inadequate?	0	4

Discussion

These preliminary tests were intended to develop the requirements for hardware, software and concept of operations of tactile cueing for air navigation. The air navigation testing did not reflect actual operational complexity. The flight paths tested were straight lines, and did not simulate threat avoidance or multi-leg routes. When using tactile information, the test parachutist demonstrated localizer and glideslope navigation to a given landing zone. These preliminary results indicated that tactile cueing for air navigation is feasible and further work is warranted. Additional tests are scheduled using the NAMRL tandem parachute system. Using the tandem system will allow testing of tactile air navigation with additional visual tasking by the subject, with the tandem instructor serving as the safety pilot.

As part of the planning for the HAHO TSAS air navigation test, informal interviews with active duty HAHO personnel were conducted. During these interviews, military personnel indicated the following interest in the navigation capabilities of the tactile display for canopy flight:

- Current glideslope indications would be especially useful for avoiding arriving at the waypoint too high.
- Left - right steering cues would assist separated team members in avoiding one another.
- Waypoint steering cues would be useful in ground operations in various situations.

In addition, active duty HAHO personnel postulated that the following additions to the TSAS-SF tactile navigation system would improve mission effectiveness:

- A mode assisting the jumpmaster in aircraft spotting.
- A mode for groundspeed indication and altitude indication below a trigger altitude for help during the landing sequence.

Preliminary results, both qualitative (Table 5) and quantitative (Figure 5) suggest that the use of the TSAS-SF for ground navigation allows the subject more “heads up” time. This “heads up” capability can improve search capability of both hostile and friendly factors. When combined with an additional visual task, tactile cues show the potential to be an effective alternative, or enhancement to visual displays. The majority of subjects preferred TSAS-SF to the visual only display, because TSAS-SF was easier to use and provided enhanced navigation. This capability would be invaluable to Special Forces operators to increase mission effectiveness. .

The results for the air and land navigation testing are in agreement with previous underwater navigation testing (McTrusty, Walters, 1997; Rupert, McTrusty, Peak, 1999). To determine the feasibility of tactile navigation in an underwater environment, a test was conducted with the Very Shallow Water (VSW) Mine Counter Measure (MCM) unit. Divers conducting VSW MCM operations must navigate using the Swimmer Inshore Navigation System (SINS) while monitoring mine detection sensor displays. TSAS was integrated to the SINS to provide underwater tactile navigation data. The subjects navigated a triangular course. The navigation cues were provided visually via the SINS display or via tactors attached to the divers’ wrists. Example data shown in figure 6 compares subject navigation tracks using both methods.

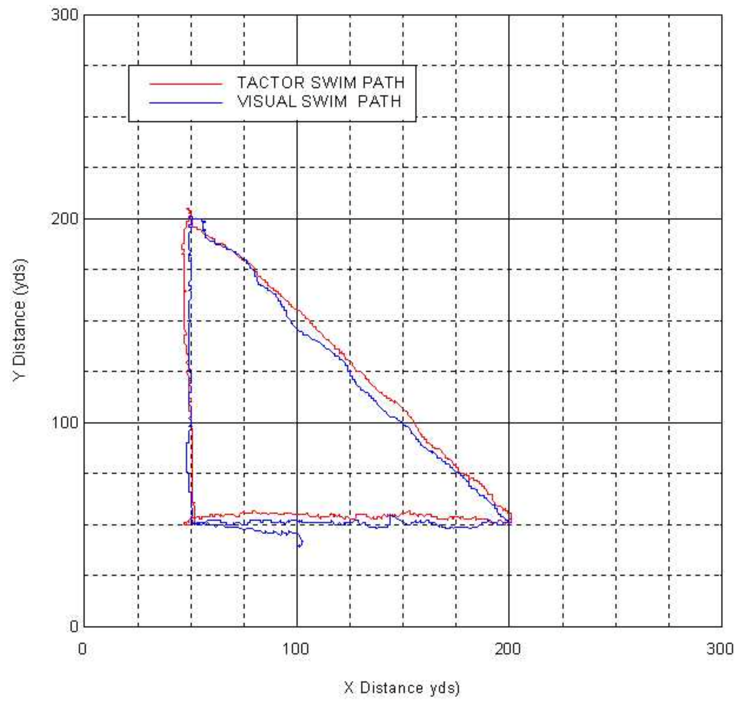

Figure 6. Example of diver navigation using either SINS-visual or tactile cues (from McTrusty, Walters, 1997).

Results of the underwater tests and subjective evaluations, showed that:

- Tactile cues were an effective alternative, or enhancement to visual displays.
- Cross track error was insignificant for both methods.
- The majority of subjects felt that TSAS was easier to use and provided enhanced navigation.
- All divers indicated that operational navigation capabilities could be enhanced with tactile technology.

Conclusions

Currently, the US military Special Forces use 2D visual navigation displays for air, ground and undersea operations. The use of a tactile display for navigation information frees the operator from a heads down position while under canopy, moving on the ground, or swimming under the water. This capability has the potential to improve performance and mission effectiveness, and reduce workload and fatigue.

TSAS hardware could be integrated into current mission equipment loads with minimal added weight or discomfort. The navigation algorithms can be easily updated to account for changing environmental conditions or mission objective parameters. Preliminary results from the air and ground navigation tests justify continued testing and evaluation to extend the capabilities of the tactile display, so that it may be used as an operational device for navigation in sea, air and land environments.

TSAS-SF, equipped with appropriate sensors, could have further Special Forces operational applications for cueing team member location and threat direction. Similarly, communication between squad/platoon members could be achieved in an intuitive, clandestine manner using a tactile display vice a traditional audio display.

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The Use of Tactile Navigation Displays for the Reduction of Disorientation in Maritime Environments

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Summary
The maritime environment can be difficult to navigate in, due to poor visual cues, leading to disorientation and the potential for operational failure. The sense of touch is often overlooked as a mode of information display, but is ideally suited to providing intuitive navigation cues. Tactile cues provide a potential method to overcome these visual limitations and provide an alternative mode of displaying information from the more common visual and audio mediums. The QinetiQ Centre for Human Sciences have developed a Navigation Tactile Interface System (NTIS) that displays navigation cues through the highly intuitive sense of touch. This has been demonstrated in high-speed boats by the setting of the blind world water speed record with the use of the QinetiQ NTIS, and underwater by the US NAMRL Tactile Situation Awareness System which allowed divers to successfully complete a navigation exercises using only tactile cues. Therefore, tactile navigation displays have the potential to reduce disorientation in maritime environments and improve operational performance.

INTRODUCTION

The maritime environment (both on and underwater) can be a harsh location for humans to function. Maritime military operations are often conducted in conditions of poor visibility (e.g. at night, in fog, and in turbid water), or poor sea conditions (e.g. sea state 4/5). This can make accurate navigation difficult, lead to disorientation and ultimately failed operations. Traditionally, navigation is a visual task, although cues may be provided through spoken instructions. Recently, the effective presentation of navigation cues via the sense of touch have been developed. Tactile cues have the potential to overcome the limitations of visual and aural cues, which are compromised by poor visibility and noisy environments. Covert operations require minimal visual and aural signatures and therefore further reduce the use of visual and audio cues. This paper discusses two military maritime scenarios requiring accurate navigation; the use of High-Speed Insertion Craft (HSIC) and Very Shallow Water (VSW) Mine Counter Measures (MCM) diving, and how tactile navigation cues may enhance orientation.

MARITIME HIGH SPEED INSERTION CRAFT

Operational issues

The potential for becoming disorientated during clear daytime navigational exercises in calm conditions, with access to modern electronic navigation aids, would appear to be difficult to comprehend. Military HSIC are required to operate at night and in poor sea conditions (>SS5) and weather conditions/visibility (e.g. fog and mist). Coxswains are therefore required to navigate accurately and maintain effective control of the craft in all conditions. Craft motion, including high levels of shock and vibration, reduces the crews ability to operate the boat, e.g. high force impacts of over 20g. Also, boat vibration in the 3 – 12 Hz range will elicit vibration within the human body further reducing the ability of the coxswain to navigate the required course.

Tactile navigation cues

The provision of non-visual navigation cues can overcome the limitations of visual cues. These cues may be obscured, and difficult to interpret and comprehend when operating in poor sea conditions. Navigation cues

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provided via the sense of touch are a highly intuitive alternative to visual and aural cues. The QinetiQ Centre for Human Sciences has developed a Navigation Tactile Interface System (NTIS) that has been used to navigate a range of craft at speeds of up to ~ 70 knots. The most effective demonstration being the establishment of the blind world water speed record.

Navigation concepts

The NTIS interprets Global Positioning System (GPS) output data to provide the navigation cues. From this data two navigation concepts have been developed.

Concept 1: *Virtual corridor*

The NTIS constructs a virtual corridor, around the direct line between predetermined way-points. The perpendicular distance that the craft is away from this direct line is known as the cross track error. The width of the virtual corridor is therefore the maximum acceptable cross track error. The corridor width is predeterminable for specific applications, e.g. long distance transits may use a relatively wide corridor, whilst the blind world water speed record used a very narrow corridor. The NTIS initiates a tactile cue (analogous to a tap on the shoulder) when the crafts crosses the virtual corridor boundary (i.e. the cross track error exceeds the predetermined criterion), analogous to driving off the side of a road and onto a rumble strip. The tactile cue is active until the operator returns to within the confines of the virtual corridor. This concept is outlined graphically in figure 1. The tactile cue can be transmitted in one of two ways, either to the side of the body that crosses the corridor wall (analogous to bumping into the corridor wall), or the cue is initiated to indicate the direction of the course correction required (i.e. if the right shoulder was tapped the individual would turn to the right).

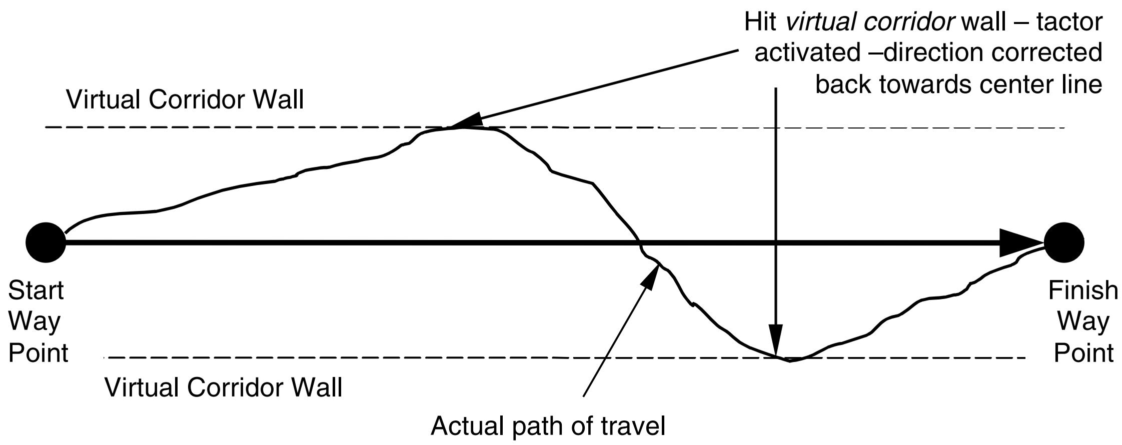

Figure 1. A graphical representation of the QinetiQ Navigation Tactile Interface System *virtual corridor* operating concept

Concept 2 : *Way-point direction indicator*

The NTIS determines the difference between the crafts heading and the direction of the target way-point. The magnitude of the tactile cue is then dependant on the magnitude of the difference between these. The greater the angle the greater the signal magnitude, i.e. if the craft is heading directly towards the way-point there will be no cue, whereas if the craft is travelling away from the way-point there will be maximum tactor activation. The magnitudes of the tactile cues are directly related to the magnitude of the angular difference. This concept has the advantage that the craft may detour from the anticipated track if required, whilst the coxswain knows in which direction the target way-point is. An example of how this concept operates is shown below in figure 2.

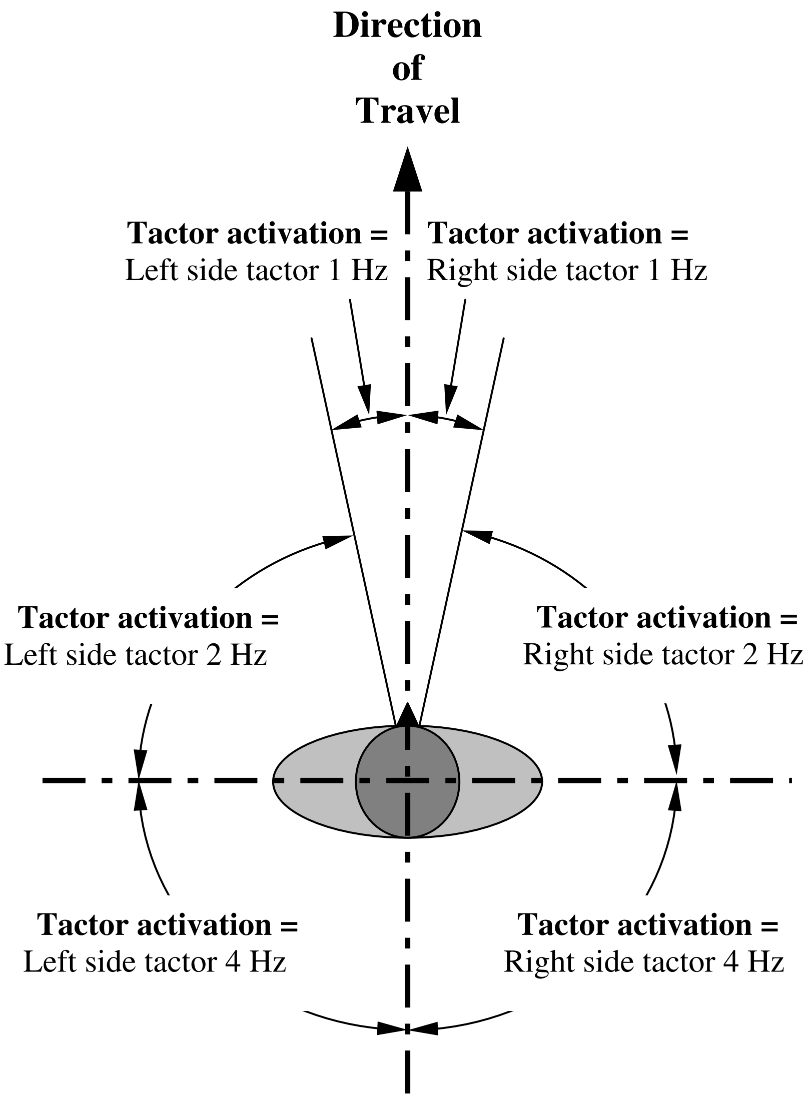

Figure 2. A graphical representation of the QinetiQ Navigation Tactile Interface System *way-point direction indicator* operating concept. Tactor activation occurring when the target way-point is not on the direct line of travel.

World Blind Water Speed Record

As part of a programme of increasing the public's awareness of blind people's abilities, Steve Cunningham established a world blind water speed record in 2000. The QinetiQ Centre for Human Sciences provided assistance for this record by providing the NTIS to increase the driver's level of autonomy. The boat used for the record attempt was a V24 'bat boat' (Ocke Mannerfelt Design), see figure 3. The design is relatively stable for a high-speed powerboat, particularly in rough water conditions. It also allows the driver and co-driver to sit alongside one another, both of which were required for a blind speed record attempt. The tactor location used for the record attempt was under the leg straps of the 6-point restraint harness used in the boat. This location provided an effective tactile stimulus whilst allowing the occupant unrestricted egress from the cockpit in the case of an emergency. The weather for the 1st attempt was poor, with a sea state of 4/5 and winds gusting to force 6. This meant that the highest average speed was only 50 mph. A second attempt was made a month later where there was minimal wind and calm water. An average speed of 73 mph was recorded, approximately ½ mph less than the sighted speed record for the V24 boat design. The use of the NTIS in establishing the blind world water speed record demonstrated that tactile cues can effectively increase the level of autonomy that blind and visually impaired people can obtain using this technology. Similarly the effectiveness and safety of sighted people may also be enhanced by the use of tactile displays.

Figure 3. The V24 power boat used to establish the Blind World Water Speed Record during the 1st attempt in conditions of sea state 4/5.

Further research

Many current tactor designs rely on vibration to provide tactile cues. Most military platforms have inherent vibration and this is particularly true of HSIC. The influence of platform vibration on tactile perception is currently unknown although there is limited anecdotal evidence on which to work from. The QinetiQ Centre for Human Sciences is undertaking a programme of work to investigate this area.

VSW MCM Diving

Operational requirement

Divers conducting future VSW MCM operations will be required to simultaneously navigate, and monitor mine detection sensor displays (e.g. sonar), whilst operating in turbid water conditions. This may be achieved using equipment such as the QinetiQ Diver Reconnaissance System (DRS), see figure 4 below. The diver must be capable of operating in conditions of very low visibility, therefore visual information will need to be presented via a head mounted display. QinetiQ trials have indicated that divers may have difficulty in navigating and searching simultaneously using visually displayed information. Subjective feedback suggested that this was due to an overloading of cognitive work capacity, and non-optimal screen symbology. Therefore a reduction in the information displayed visually to the diver is likely to improve operational performance. The presentation of navigation cues by the sense of touch is a concept through which diver performance may be enhanced.

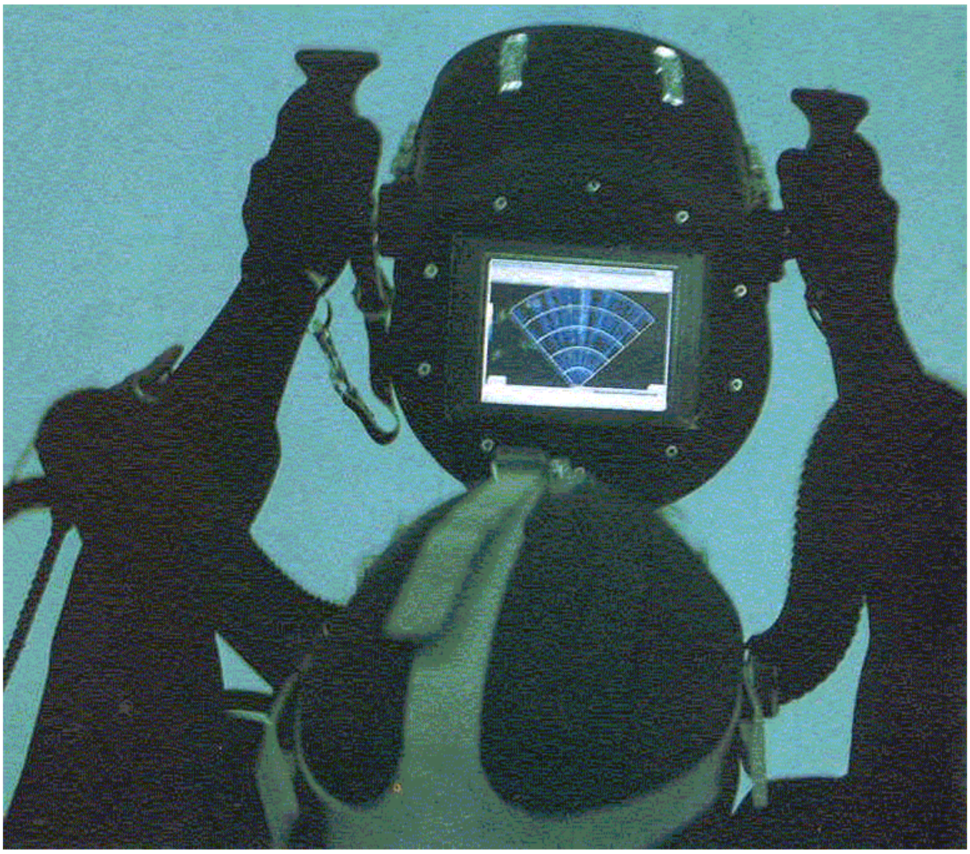

Figure 4. The QinetiQ Diver Reconnaissance System being used by a Royal Navy diver

Diver tactile navigation cues

Tactile navigation cues can be highly intuitive and in particular circumstances may be preferable to visual or audio cues. An example of this was the successful demonstration by the US Naval Aviation Medical Research Laboratory, Tactile Situation Awareness System (TSAS) programme of diver navigation in the VSW environment using a tactile navigation system interfaced to the Swimmer Inshore Navigation System (SINS). The divers navigated a triangular course, in good visibility, with position data being stored within the SINS and then downloaded after each trial. The navigation cues were provided visually or via tactors attached to the divers wrists. General observations indicated a similar cross-track error between using visual or tactile cues. Subjective feedback from the divers suggested that tactile cues may be more effective than visual cues. Example data is shown in below in figure 5 which compares the navigation tracks of diver using visual and tactile cues.

From the results of the SINS/TSAS trials and subjective evaluations it was concluded that:

- Tactile cues were an effective alternative, or enhancement to visual displays.
- Underwater navigation cross-track error (deviation from the baseline navigation course) was insignificant for both the visual only, and tactile displays.
- The majority of divers felt that the tactile display was easier to use, provided enhanced navigation, and preferred the tactile display over the visual only display.
- All divers indicated that operational navigation capabilities could be enhanced with tactile technology.

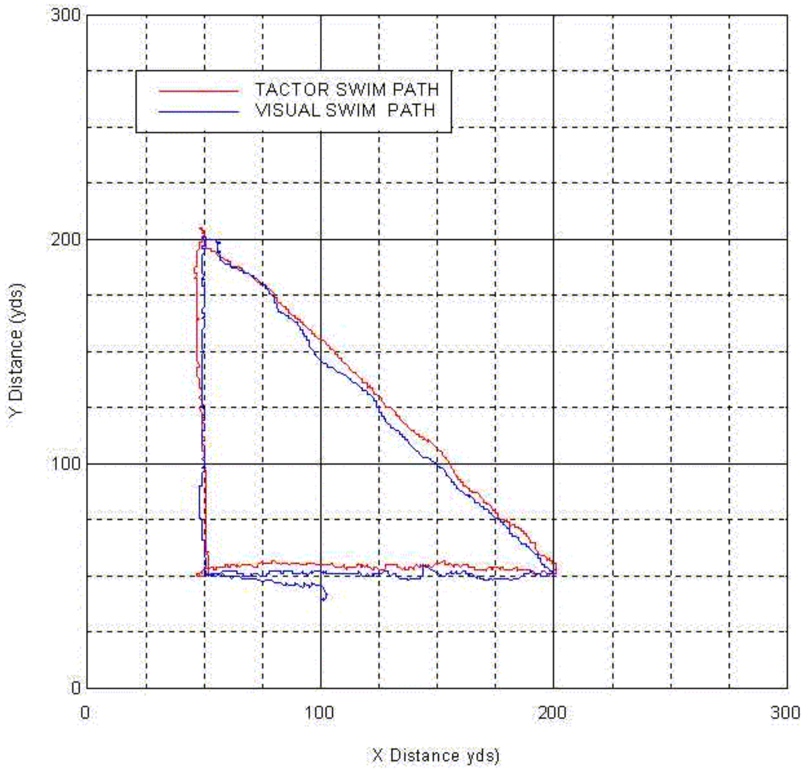

Figure 5: Example of diver navigation around a triangular course using either visual or tactile cues from the Swimmer Inshore Navigation System (SINS).

Further research

The concept of the QinetiQ DRS is a self-contained system, therefore tactile cues are presented through the DRS handles as opposed to independent tactors attached to the wrists as used on the SINS/TSAS system. Current research is establishing the optimum tactile presentation scheme, and particularly its integration with the visual sensor display to minimise cognitive workload. This may allow divers to effectively navigate and search simultaneously.

CONCLUSION

The trials conducted demonstrate that the concept of tactile navigation displays can be effective at improving navigational accuracy in hostile maritime environments. Further research is establishing the human factors that underpin the effective development of tactile interface systems such as the intuitive presentation concepts of navigational cues, the optimisation of the tactile communication devices (tactors), and the application specific requirements of individual platforms/vehicles.

The QinetiQ Tactile Information Displays programme is funded by the Chemical Biological Defence and Human Science Domain of the MOD's Corporate Research Programme.

Spatial Disorientation: Towards International Standardization

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Summary

Spatial Disorientation (SD) remains an important source of attrition in both military flying and general aviation. Several recent symposia and technical meetings have recommended various initiatives to control this hazard such as improvements in training and the standardization of mishap and incident data. In the first area, improved and standardized methodologies of training with appropriate training objectives for aircrew training in SD are intended to produce curricula that will provide international air forces with the ability to ensure that aircrew have a common training base. In the second area, the development of a standardized method of data collection, terminology and reporting for SD related topics would enable a common accident database from which factors involved in the SD accident or incident can be determined. Similarly, a standardized format for data collection from surveys of aircrew experience of SD would be extremely useful for comparative and education purposes. Ultimately, research into SD and the application of training countermeasures can be better coordinated, and more effectively and economically applied. Such enhancements are already being progressed in the military forum through the Air Standardization Coordinating Committee (ASCC). Other international services and organizations (NATO in particular) could readily adopt many, if not all, these initiatives. This paper summarizes the achievements to date and outlines the way in which other organizations can both benefit from the work already achieved, and also contribute to the anticipated improvement in mission effectiveness and flight safety.

INTRODUCTION

Spatial Disorientation (SD) is not a new problem to aviation but judging from the concerns expressed in the open literature there is evidence that the phenomenon continues to be a most important source of attrition in all air forces. SD contributes to between 15 and 30 percent of aircraft accidents, and SD incidents reduce operational effectiveness [1].

There is encouraging evidence that operators are beginning to realize that this hazard, which is primarily due to the limitations of man's orientation senses in flight, is worthy of attention and the application of countermeasures. However, the research and development resources to address the issues have been severely restricted over recent years.

Prevention of SD is the ultimate aim and standardization of many issues is likely to contribute significantly to this aim. It was with these ultimate goals in mind that in 1996 a proposal was made to the Air Standardization Coordinating Committee (ASCC) to form a project to address SD [2]. The following year, a Project Group (PG 117) was formed in Working Party (WP) 61 of the ASCC and the work produced so far is encouraging.

THE FUNCTION OF ASCC AND WP 61

NATO members and PfP nations may not be familiar with the function of ASCC and so the following summary is provided [3]. The ASCC nations are Australia, Canada, New Zealand, United Kingdom and the United States.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

The **mission** of the ASCC is to ensure that member nations are able to fight side by side as airmen in joint and combined operations. Interoperability is the ability of coalition forces to train, exercise, and operate effectively together, in the execution of assigned missions and tasks. Within available resources, the ASCC mission of interoperability is achieved through standardization, validation, economizing the use of resources, and information exchange.

- **Standardization**. Standardization is not an end in itself, but is a tool for increasing the operational effectiveness of coalition military forces. Its primary purpose is to achieve operational standardization requirements; however it may also be used to promote economy in the use of resources. International standardization agreements are implemented through national documents. There are three levels of standardization.

    - **Compatibility**. The suitability of products, processes or services for use together under specific conditions to fulfil relevant requirements without causing unacceptable interactions.

    - **Interchangeability**. The ability of one product, process or service to be used in place of another to fulfil the same requirements.

    - **Commonality**. The state achieved when the same doctrine, procedures, or equipment are used.

- **Validation**. Validation assesses the extent to which ASCC member nations have achieved the operational standardization requirements and focus on assessing the capability for combined air operations. Validation is conducted through the following activities:

    - Analyzing the lessons identified/learned during operations and exercises.

    - Assessing the relevance, adequacy and effectiveness of existing standards.

    - Confirming that national implementing documents reflect ratified Air Standards.

    - Testing interoperability during exercises or operations.

- **Economical Use of Resources**. The ASCC provides opportunities for both formal and informal collaboration on issues of common interest to air forces, thereby sharing successes and avoiding duplication of effort. The following activities may be conducted where they improve national or coalition capabilities, while reducing overall costs:

    - The loan of equipment through the Test Project Agreement programme.

    - Collaborative activities not covered by other organizations.

    - Standardization of equipment or procedures not directly related to combat operations, where this is expected to result in significant savings and/or improvements to flight safety.

- **Exchange of Information**. Formal and informal exchanges of information improve the operational effectiveness of national forces, which in turn improve the capability of coalition forces. They also contribute toward ASCC goals by:

    - Enhancing interoperability, where standardization is inappropriate or where individual national requirements preclude standardization.

    - Determining the viability of proposed standardization projects.

    - Assisting in the development of subsequent Air Standards.

PUBLICATIONS

There are three levels of publication that support the standardization initiative. In hierarchical order, they are as follows:

- AIR STANDARD (AIR STD). An ASCC AIR STD is a formally documented agreement between ASCC members to standardize specific military doctrine, procedures and/or material to enhance their ability to conduct joint and combined operations.

- ADVISORY PUBLICATION (ADV PUB). An ASCC ADV PUB is developed where agreement to standardize is either impracticable or inappropriate yet there remains a requirement for nations to be advised of the procedures and materiel being used by other ASCC nations.

- INFORMATION PUBLICATION (INFO PUB). An INFO PUB is an ASCC document for the formal exchange of information between nations which does not meet the requirements of AIR STDs or ADV PUBs.

Publications may be authorised for release. Requests for further release within ASCC nations should be addressed to the national Assistant for Standardization (A/Stand); other requests should be addressed to the ASCC Management Committee (Email: asccad01@pentagon.af.mil). All requests should state the purpose for which release is requested. Contact details are available on the ASCC Website at http://www.xo.hq.af.mil/xor/xorg-iso/ascc/

Within ASCC, Working Party 61 is responsible for addressing Aerospace Medicine, Life Support and Aircrew Systems and Project Group 117 specifically deals with SD issues.

PROJECT GROUP 117

The **objective** of Project Group 117 is to standardize concepts, doctrines, procedures, equipment and designs to enhance aircrew effectiveness by minimizing the impact of SD in order to maintain the specified coalition capability requirements. The Project Group's **scope** is to develop AIR STDs, ADV PUBS and INFO PUBS concerned with SD in the flight environment in the following areas:

- Training and operational issues.

- Standardization of terminology and epidemiological data.

- Methods and equipment to enhance, maintain and regain spatial orientation in flight, and other countermeasures to SD.

Co-operative investigations are coordinated and liaison is maintained with appropriate Project Groups, Working Parties and other agencies.

The aim of these publications is to improve the effectiveness of ASCC forces in joint training and combined operations by minimizing the impact of SD through the reduction of loss of lives and money. The capability of joint operations will be enhanced by ensuring commonality in the presentation of orientation information and procedures to prevent and overcome SD.

The Project Group has two primary projects and several information exchange items. These are summarised below and the progress in each area is described.

PROJECT: CONTROLLING THE HAZARD OF SPATIAL DISORIENTATION FOR COMBINED JOINT AIR OPERATIONS THROUGH ENHANCED TRAINING.

Objective: To develop standardized curricula with appropriate training objectives for aircrew training in SD.

Scope: Project Officers will exchange data and information to enhance interoperability in order to develop standardized objectives in both ground-based and in-flight demonstration and training in SD. The goal is to produce standardized curricula that will provide ASCC nations with the ability to ensure that aircrew have a common training base.

AIR STD 61/117/1: Aviation Medicine/Physiological Training of Aircrew in Spatial Disorientation.

The intent of this standard is to define the minimum aviation medicine/physiology training in SD of aircrew of each ASCC member nation. Training which meets the requirements of this AIR STD will be acceptable to all ASCC member nations for the purpose of allowing trained aircrew from any ASCC nation to operate that nation's aircraft. The AIR STD provides a standardized academic definition for SD, specifies details of the required (and agreed) classroom curriculum and makes general recommendations about ground-based and in-flight demonstration and training. It is a very useful document that has already provided the basis for further publications on standardization. AIR STD 61/117/1 has been ratified and is fully releasable to other agencies.

Draft AIR STD: Ground-based demonstration in Spatial Disorientation.

The objective of this AIR STD is to define a standardized curriculum and practice for the ground-based demonstration of the limitations of the orientation senses and SD. From information provided by Project Officers, it is clear that a variety of devices are being used and, although **general** training objectives in SD are available, **specific** objectives for the ground-based demonstrations are not used. Although it is not possible to provide commonality of experience with the variety of devices currently in use, it has been agreed that **common** training objectives would be valuable. These training objectives should reflect best practice and will not be written with specific devices in mind. The agreed objectives could then be used to define the future performance criteria of SD demonstration devices. This AIR STD is in early draft form but progress is being made and the publication will be progressed.

Draft AIR STD: In-Flight Demonstration of the Limitations of the Orientation Senses and Spatial Disorientation in Rotary-Wing Aircraft.

The objective of this AIR STD is to define a standardized curriculum and practice for the demonstration of the limitations of the orientation senses and SD during an in-flight rotary-wing demonstration. An additional intent is to standardize the method of training those who are to conduct the demonstration (training the trainers). The AIR STD also serves as a reference document for trainers. It is therefore comprehensive in its approach. The publication is based upon the successful programme that has been conducted by the British Army for over 20 years [4]. Although the publication has yet to be ratified and so is not yet releasable, this is anticipated for later in 2002. Nevertheless, the demonstrations and their efficacy are described in the open literature [5,6].

Draft AIR STD: In-Flight Demonstration of the Limitations of the Orientation Senses and Spatial Disorientation in High Performance Fixed Wing Aircraft

The objective of this AIR STD is to define a standardized curriculum and practice for the demonstration of the limitations of the orientation senses and SD during an in-flight high performance fixed wing demonstration. The AIR STD also serves as a reference document for trainers. It is therefore comprehensive in its approach. The procedures have been recently developed in the UK on the Hawk T Mk 1 training aircraft of the Royal Air Force but are also being assessed by other air forces. Although the publication has yet to be ratified and so is not yet releasable, this is anticipated for later in 2002.

Draft AIR STD: In-Flight Training in Spatial Disorientation.

The objective of this AIR STD is to standardize the in-flight training of SD in both fixed and rotary-wing aircraft. Most air forces already incorporate some training of this sort but standardization of the training objectives will be of great benefit in providing a common training base for aircrew on joint and combined operations, the goal being a commonality in experience and expertise. The AIR STD specifies that training is to be conducted during both elementary and advanced (including operational conversion) flight training, and also during conversion to each specific aircraft type. An assessment of skills should also be made during revalidation of an instrument flying rating. Although the publication has yet to be ratified and so is not yet releasable, this is anticipated for later in 2002.

PROJECT: IMPROVING UNDERSTANDING OF SPATIAL DISORIENTATION THROUGH COMMONALITY OF TERMINOLOGY, REPORTING PROCEDURES, AND RESEARCH METHODOLOGIES.

Objective: To develop a standardized method of data collection, research methodologies, terminology and reporting for SD-related topics.

Scope: Project Officers will exchange data and information to achieve commonality in SD-related topics. The goals are to produce:

- An accident database from which factors involved in the SD accident or incident can be determined.
- A standardized format for data collection from surveys of aircrew experience of SD.
- Standardized approaches to research methodologies.

These products will provide ASCC nations with the ability to compare data, and in turn, target future research efforts in order to minimize the impact of SD in joint and combined air operations.

Draft AIR STD: The Contribution of Spatial Disorientation to Accidents and Incidents.

The objective of this AIR STD is to define the data to be collected for accidents and incidents in which SD is implicated. Once data collection is standardized between ASCC nations and services, this research tool will enable data to be compared and contrasted between services and nations and thus enhance the collective effort towards controlling the SD hazard. The aims of this data collection are summarized as follows:

- To gather information on the incidence of various factors that affect the generation of the SD accident or incident.
- Identify aircrew member, aircraft and mission factors that contribute to the SD accident or incident.
- Identify controls that could be applied to prevent or overcome SD, e.g. training, technology, ergonomics, etc.

Accident investigation techniques are not standard between ASCC nations and are constantly evolving. Therefore, rather than attempt to re-categorize all accidents, a standard format provided as an annex for data collection specifically concerning the accident or incident in which SD is implicated is provided in addition to existing accident analysis methods. The annex will be completed by aeromedical professionals (e.g. flight surgeon, physiologist, psychologist or researcher) preferably at the time of the accident or incident. If this is not possible, it will be completed once the proceedings of the investigation have been finalized. At “worst” it will be a valuable research tool for the retrospective analysis of accidents. Data analysis will be a national responsibility unless a collaborative agreement is established. When data are exchanged between services and nations, the originating service or nation’s regulations on confidentiality and security will be applied. This is a very useful document that has already provided a valuable means of data collection. The AIR STD is still subject to the ratification process and should be releasable to other agencies in the near future.

INFO PUB 61/117/5: SD Survey Postal Questionnaire

The objective of this INFO PUB is to ensure that each member nation can record aircrew SD survey data in a standard format. It has been decided that 2 formats should be developed; a postal questionnaire that could be sent to a large number of pilots, and an administered questionnaire that could be used to obtain more detailed information from a smaller number of participants. Information obtained from use of these questionnaires will be made available to member nations to enhance understanding of SD problems faced by aircrew. This information will be of value in developing future standards for the protection of aircrew. Nations agree to exchange information derived from use of this postal questionnaire with other member nations and identify enhancements to the questionnaire that could improve its utility in future. UK and USAF have already successfully used the questionnaire and their initial experiences are recorded elsewhere in these proceedings [7,8]. INFO PUB 61/117/5 has been agreed by the national Coordinating Members and is fully releasable to other agencies.

INFORMATION EXCHANGE: MINIMUM REQUIREMENTS FOR CONTINUOUS PRESENTATION OF ORIENTATION INFORMATION.

Objective: To specify the minimum requirements for continuous presentation of orientation information to aircrew in head-up and helmet-mounted displays particularly when the field of regard is off bore sight

Scope: The goal is to conduct a literature search and collate information on the state of current and projected technology. Once this is achieved, progress towards standardization can be made in the equipment (including display symbology, etc) and procedures both to maintain and regain spatial orientation.

This Information Exchange is in early draft form but progress is being made and the publication will be progressed.

INFORMATION EXCHANGE: MEDICAL FACTORS PREDISPOSING TO SPATIAL DISORIENTATION.

Objective: To identify those medical factors which predispose aircrew to SD.

Scope: Traditional teaching emphasises the relevance of various physiological, psychological, pathological and pharmacological factors to an increased incidence of SD. However, the source of this information is poorly coordinated. This Information Exchange will catalogue these factors under a single cover in order to enhance the control of SD in joint operations. An INFO PUB should be ready by late 2002.

THE WAY FORWARD

This paper has provided details of the important ways in which standardization of various aspects of SD can be achieved in an international forum (ASCC). The primacy of effort of work of Project Group 117 has been directed towards the identification of aspects of SD that are amenable to standardization. Nevertheless, some significant progress has been made in a short time and the initiatives have provided valuable tools in the areas of training and data collection. The following points are stressed:

Training. Common practices between nations should be based on the BEST practise. If this can be achieved, we will know that each other has aircrew that are “safer” to fly through our own airspace or on joint operations. In particular, standardization of the training objectives will be of enormous benefit in providing a common training base for aircrew on joint and combined operations, the goal being a commonality in experience and expertise.

Data collection. Many nations have very small air forces or services. By pooling our data in a common format we can increase the power of our observations. In particular, the smaller organizations can gain from the experience of the bigger ones who in turn will gain from this approach as it may provide a fresh look at the challenges. The ultimate aim is of course to provide the EVIDENCE BASE upon which to build our cases for recommendations to enhance mission effectiveness and flight safety.

Some of the ASCC experiences in SD have been submitted to the NATO National Agency for Standardization for incorporation in STANAGS (particularly STANAG 3114: Aeromedical Training of Flight Personnel, and STANAG 3318: Aeromedical Aspects of Aircraft Accident/Incident Investigation) but there would be distinct advantages if broader liaison were established so that NATO and PfP nations can benefit.

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Postural Stability in Pilots Under Vestibular Stress – A Comparative Look at Pilot Candidates Versus Experienced Jet-Aircrews

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Introduction: All Air Forces battle the lack of sufficient recruitment of pilot and aircrew candidates. One way to solve the problem is to look into extending the flying career of an individual. German regulations require jet aircrew members - except those in commanders' positions - to stop flying at the age of 41 and leave the Bundeswehr to pursue a civilian career. This means the loss of experienced aircrews not because of medical problems but because of legal requirements. This age restriction of 41 might not be justified any more from a medical point of view. Aeromedical specialists all around the world are looking into the issue of aircrew aging.
Orientation in space and postural control are very important for any aircrew. In this study we compared the postural control of experienced pilots versus pilot candidates. We tried to determine possible differences between the age groups to get an indication of the ability to control one's position in space after a strong vestibular stimulus. As a working hypothesis, we assumed that there would be no significant differences between the two groups of test persons.

Methods: In Div. III of the German Air Force Institute of Aviation Medicine we looked into the postural stability of pilot candidates versus experienced jet pilots after subjecting them to a strong vestibular stress induced by the Flight Orientation Trainer (FOT). The FOT was installed in Fürstenfeldbruck in 1994. Its fully cardanic gondola with its cockpit is mounted on a 30 ft planetary arm.

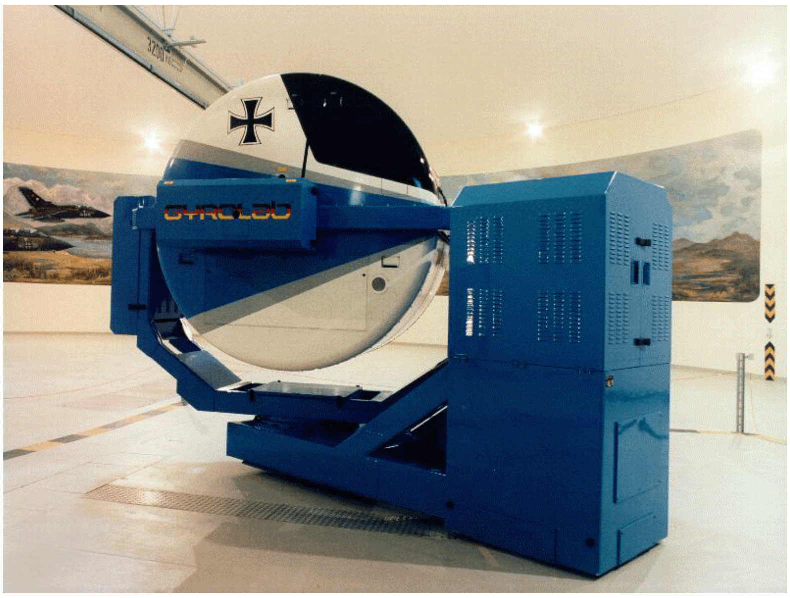

Figure 1: The Flight Orientation Trainer

The Flight Orientation Trainer with its ability to rotate freely in space around all three axes can stimulate the vestibular and otolith organs. Especially coriolis effects can be generated by rapidly changing the rotational plane.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

The test persons were rotated about their yaw axis at 120°/sec or 20 RPM and at the same time on the planetary arm of the FOT at 150°/sec or 15 RPM. Each trial lasted exactly 180 sec and ended abruptly with a simultaneous deceleration in both axes, inducing a strong coriolis effect. The time of continuous motion lasted approximately 150 sec.
Before entering and after exiting the FOT the test persons were guided to the posturography. The distance from the FOT to the posturography was 25 meters. The time between the end of the FOT run and the start of the posturographic measurement was approximately 90 seconds.

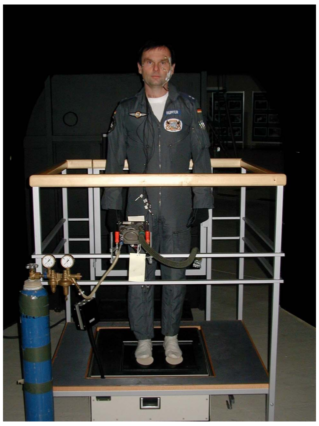

Figure 2: Posturography

The posturography made by the Thoennies company measured body sway in anterior/posterior and lateral direction as well as the area covered. For that purpose the test persons had to stand still in a relaxed posture on the platform. For all measurements the test persons had to remove their shoes. Postural control and stability was measured over a period of 120 sec comprising 6 measurement periods of 20 sec each. Measurements were performed with eyes open, respectively with eyes closed. During the 'eyes open' data recording the test persons could see a fixing cross at 3m distance at eye level. Piezoreceptors in the measuring platform sensed the shift of body weight and sent these electronic signals to a computer. The data were computed and displayed in numeric tables and viewgraphs for distance and area covered.

Before and after the test runs the test persons were also questioned about their well-being, and basic physiological parameters were measured (heart rate, blood pressure).

Personnel that took part in the study included 21 male test persons: 10 experienced jet aircrew members between 39 and 50 years old with an average age of 43.5 years (43.5 ± 4.0) and 11 pilot candidates between 20 and 25 years with an average age of 21.7 years (21.7 ± 1.4). The experienced pilots participated during their tri-annual flight physical at the GAF Institute of Aviation Medicine. The pilot candidates had passed all initial aeromedical and psychological testing and were waiting to start their flight training. Informed consent was obtained from all test persons.
Statistical calculations of the p-values were done by means of the Student T-Test.

Results: It is known that – regardless of age groups – there is a significant difference in the values for posturographic measurements with eyes open or eyes closed. In the tables below, the x-axis depicts the regristation phases 1, 2 and 3 for eyes open or eyes closed measurements before and after the FOT run. The y-axis shows the area covered in cm²/sec for the respective measurements. The rhombic marks indicate the values before ("PRAE"), the square marks indicate the values after ("POST") the FOT runs. Age group <30 years represents the pilot candidates, age group 30<50 years represents the experienced pilot group.
None of the test persons fell out of the "clinical envelope" of the normal posturographic range. None of the test persons suffered from motion sickness during or after the test.

In Table 2 the values for the pilot candidates with eyes open are depicted. It shows that the area covered after the FOT run is greater than before. It also shows that the values decrease as time passes after the vestibular stress.

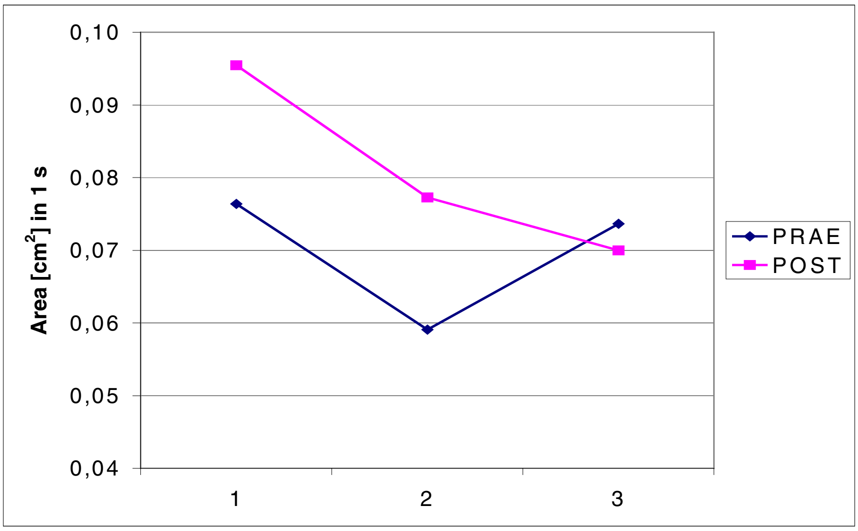

Table 2: <30 Years, eyes open (means, n=11)

Table 3 shows the values for the area covered for the measurements with the eyes closed for the pilot candidate group. Values taken after the FOT run are initially much higher than before the run and as compared to the measurements taken with eyes open. As time passes after the stimulus they nearly reach the same values after approximately 210 sec.

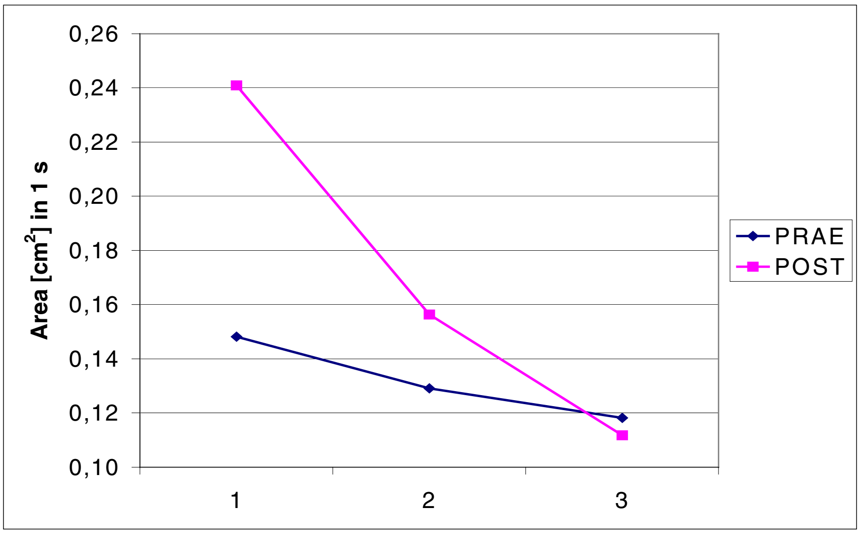

Table 3: <30 years, eyes closed (means, n=11)

For the 30<50 years age group, Table 4 depicts the values for the measurements with eyes open before and after the FOT runs. The values between before and after the FOT run show a different level. The value for the second measurement is in both cases higher than that of the first measurement. Whereas the value of measurement 3 "prae" remains higher than measurement 1, the value of measurement 3 "post" is decreased in relation to measurement 1.

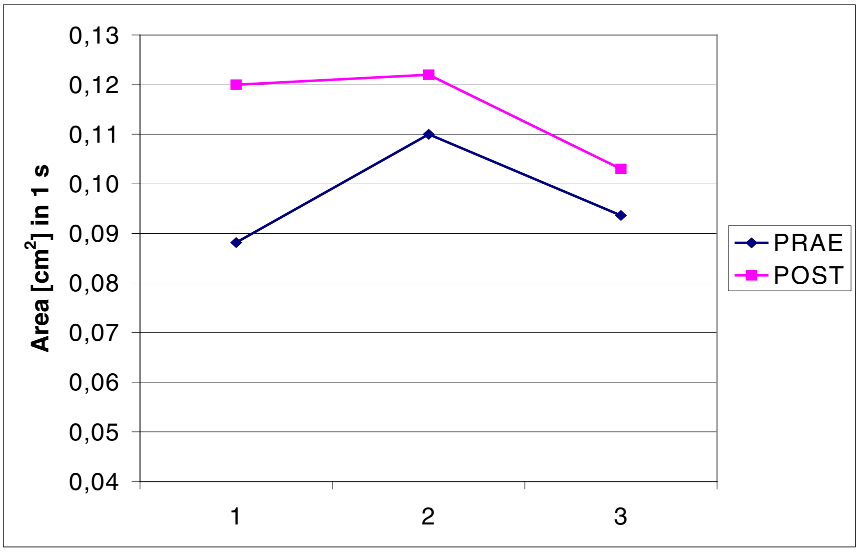

Table 4: 30<50 years, eyes open (means, n=10)

In Table 5 the values for the experienced pilot group with eyes closed are shown. The values of all measurements before and after the FOT run remain at different levels during all registration phases. Although the value levels are clearly separated, a statistically significant difference could not be found.

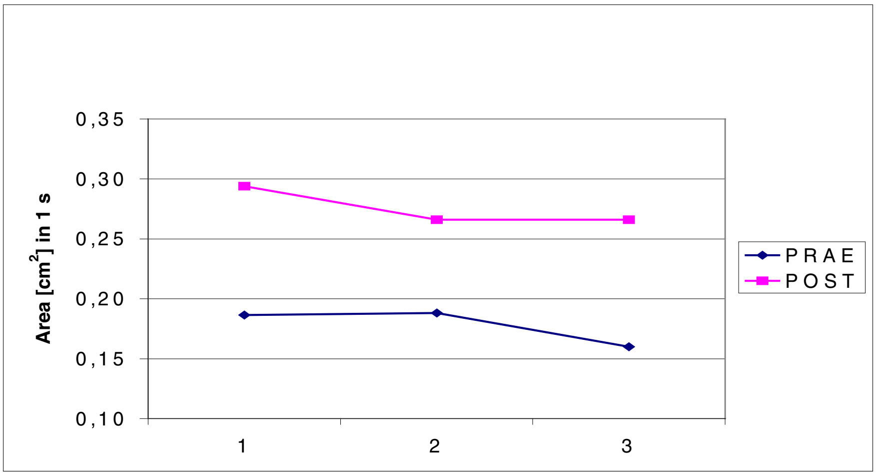

Table 5: 30<50 years, eyes closed (means, n=10)

Table 6 shows the comparison between the two groups of test persons. Only the values for the area covered after the vestibular stress by the FOT run show significant differences for the age groups.

	Time	Eyes	Difference	P-Values
Dist.	PRAE	closed	0,0042	0,9736
		open	0,12	0,91
	POST	closed	0,0815	0,6151
		open	0,0498	0,4679
Area	PRAE	closed	0,09	0,1565
		open	0,0276	0,0979
	POST	closed	0,15	0,0435
		open	0,0341	0,0209

Table 6: Comparison of age groups (<30 years and 30<50 years); P-Values for differences of the mean

Discussion: The purpose of this study was to get an indication if there might be differences in age and experience groups with regard to the compensation of vestibular stress.
In our working hypothesis we assumed that there would be no significant differences between the two groups of test persons.
Generally, the pilot candidates seemed to be less affected by the vestibular stimulation. They recovered to baseline faster than the experienced pilots. The absolute values were lower for the pilot candidate group before and after the FOT run. Only the "area" measurement was significantly different in both groups but generally the results show a tendency towards a longer recovery period for the experienced pilot group. Unfortunately, the number of test persons is small because experienced jet aircrews are hard to include in a study that is performed in addition to their regular flight physical.
An additional problem was the distance between the FOT and the posturography. It was 25m. In the approximately 90 sec between the end of the vestibular stress induced by the FOT and the starting point of the first measurement, a lot of the effect is lost and a stabilization of the vestibular regulation has already taken place. This could clearly be seen because many test persons of both groups could not walk a straight line without help directly after exiting the FOT. Unfortunately, this effect was nearly washed out before the first measurement was taken.
Although the vestibular stimulation lasted for 180 seconds, all test persons described the sudden deceleration from a continuous motion as the strongest stimulus. A test profile that provides more short-term accelerations and decelerations would increase the coriolis-like vestibular stress, which could be more effective than just the continuous motion around more than one axis.

Conclusions: The results indicate that vestibular stress might affect older aircrew members more than pilot candidates. The significant differences in the area measurements after the 'vestibular stress and eyes closed' have to be verified with a larger sample size.
It appears that motions inducing a coriolis effect are more effective in inducing vestibular stress. For that purpose the FOT profile should be redesigned to produce these effects.
To more directly register the effect of the vestibular stimulation, time and distance between FOT and posturographic measurement have to be shortened.
At this point our results do not indicate that the vestibular regulation in the older test group might be insufficient for these pilots to continue to fly jet aircraft.

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G & α: Centrifuge Occupant Tolerance to Simultaneous High G and High Angular Acceleration

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Summary
The ability of a centrifuge operated as a Dynamic Flight Simulator to meet the response recommendations of the Federal Aviation Administration (FAA) for motion simulators is discussed. The effect on an occupant of angular acceleration artifacts produced by such an enhanced centrifuge is explored. The concern investigated herein is whether these high angular acceleration artifacts are dangerous, disorienting, or distressing. Human response tests have been conducted on the centrifuge at Wright-Patterson AFB to evaluate sensitivity to the artifacts produced by a centrifuge when operated in this rapid response mode. Results indicate the effect to be no more than a mild disturbance over the expected range of G loading and artifact magnitudes found in the next generation of centrifuges. The unique capability of a Dynamic Flight Simulator is that the pilot can be exposed to high fidelity, sustained, elevated-G levels while receiving training in flight procedures and air combat tactics. Such a capability would be expected to provide improved flying performance during the vestibular and tactile misinterpretations common during sustained acceleration.

Introduction
Ground-based motion simulation of aircraft is currently accomplished with “six-post” or “hexapod” devices. These devices are able to provide motion cues with little addition to the response time a pilot senses. These devices are particularly suited to provide motion cues for aircraft operations (such as landing tasks) where pilot response is critically dependent on the fidelity of the visual and motion cues. Hexapod devices (Figure 1) are not able to provide sustained acceleration. This means that flight fidelity is diminished in many maneuvers such as a basic coordinated turn or critical tactical maneuvers of fighter/attack aircraft. This missing fidelity impacts training pilots to cope with vestibular and tactile illusions that routinely occur in flight, especially at low, but not momentary, inertial forces. Centrifuge-based flight simulation offers the potential to provide sustained G flight simulation. The most fundamental challenge is to provide rapid response with a massive device: 1) whose controlled inertia includes a planetary arm as well as the cockpit capsule (referred to in this paper as the cab); and 2) whose changes in acceleration level result in acceleration artifacts, namely angular accelerations associated with cab rotation, that may degrade the rider’s perception of flight. These issues are closely coupled, because rapid response times result in high angular acceleration artifacts. The concern investigated herein is whether these high angular acceleration artifacts are dangerous, disorienting, or distressing.

<u>Definition of Dynamic Flight Simulation</u>
Dynamic Flight Simulation (DFS) is defined in this paper to be operation of a centrifuge as a flight motion simulator with the centrifuge driven by pilot commands in response to a perceived flight condition [1]. It is similar to a hexapod motion simulator in that a pilot provides closed-loop response to out-the-window visual cues, instrument readings and perceived motion cues that have been coordinated to represent aircraft flight. Fidelity of the simulator’s response time and accelerations to that of the actual aircraft is critical, as is accurate relative timing of this sensory information to the pilot. The implications for ideal operation are that the math model of aircraft response must compute instantaneously and the centrifuge should respond instantaneously to the math model output [2].

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Tracking delay is the sum of the transport lag and the delay in centrifuge response. Reducing delay is the result of design improvements, such as increased speed of the computational hardware and software as well as increased motor size and reduction of centrifuge mass in motion. Federal Aviation Administration Circular 120-40B specifies how much motion and visual tracking delay can be tolerated in simulators used to train commercial pilots [3]. The simulators for which these specifications were written are hexapod devices that impart only onset acceleration cues that are "washed out" within a fraction of a second [4]. Hence, it does not address the issue of how much lag is suitable for a pilot experiencing periods of sustained acceleration levels above 1 G. It is likely that the pilot will be less sensitive to lag at elevated G levels, but this is a conjecture on the part of some of the authors that needs to be evaluated with human response tests on a rapid response centrifuge.

An improved controller design that is expected to make modern centrifuges capable of satisfying the most strict FAA category recommendations is discussed in another paper by the authors [5]. The correlate of implementing such a control system would be the introduction of very fast repositionings of the cab and thus very high angular accelerations and decelerations imposed on the pilot within. Large angular cab excursions are required because the tangential component of centrifuge acceleration becomes more influential in determining direction of the resultant centrifuge acceleration vector. It is possible that such rapid angular movement, even when coordinated with the desired linear accelerations, may be dangerous without proper restraints, disorienting to the point of disability, distressing to one's stomach, or otherwise intolerable. This paper describes a brief investigation into the human sensitivity to such rapid angular accelerations at several linear G levels in all three axes (x, y, and z).

Methods

The objective of the tests described herein was to develop a subjective assessment of human perceptual sensitivity to artifacts of angular and linear acceleration at various G loadings. The magnitudes of the angular artifacts investigated were selected to cover the range of angular rates produced in the mathematical model used for the simulator's control system design (1). The tests were conducted with no task distractions in order to obtain the unmasked sensitivity.

Overall Equipment Set-Up- The Dynamic Environment Simulator (DES, Figure 2), a man-rated centrifuge at Wright-Patterson AFB, was set up in two different configurations: seat facing forward in a tangential direction for roll exposures and seat facing inboard radial for pitch exposures. The visual field consisted of a projected text on a white screen in a dark cab and operation of the flight stick. The seat had a 30° seat back angle. The DES arm speed and cab position were under open-loop computer control with G force experienced in two axes simultaneously. Gz onset rate was the maximum obtainable with arm torque (approximately 0.75 Gz/sec).

Subjects- The test subjects were volunteer members of the DES Sustained Acceleration Research Panel, and had passed all required medical screening and completed indoctrination training. They gave informed consent and were trained in the verbal responses required for measurement.

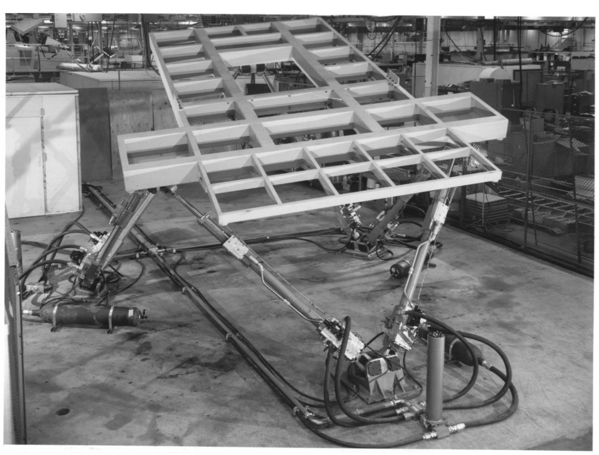

Figure 1. A hexapod motion base.

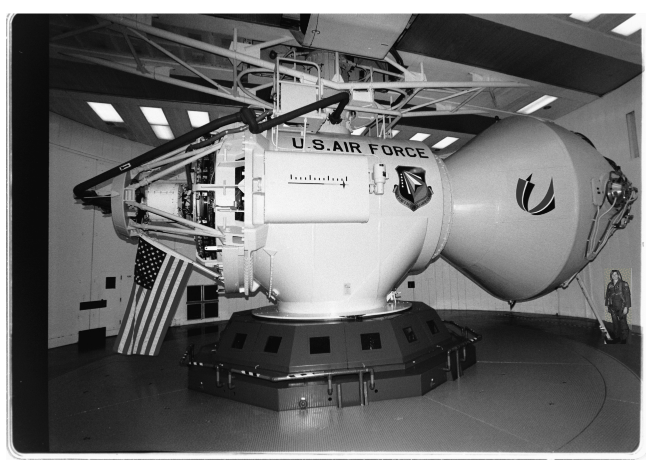

Figure 2. Dynamic Environment Simulator

Experimental Procedures- Subjects were exposed to a series of 0.75 Gz/s onset ramps to plateaus at 1.4, 2, 4, 6, and 8 Gz as well as a control condition at 1 Gz. The plateau lasted 12 seconds. During the plateau, they also experienced a roll pulse. During plateaus at 4, 6, and 8 Gz the pulse was sustained for 4 seconds while during plateaus at 1, 1.4, and 2 Gz it was momentary. The magnitude of the pulse was varied according to Table 1 and the onset of the pulse was at a set alpha rate of 1, 2, 4, 7, or 10 radians per second squared, also found in Table 1 (note each separate test profile is designated by a letter). The entire table of conditions was repeated in the pitch axis. There were 7 subjects, each experiencing 3 repetitions of the tests described above. After returning to baseline, subjects verbally responded with a numerical indication of the intensity of the perceived artifact. The Artifact Response Rating (ARR) scale was:

0 = did not feel at all
2 = noticed it
4 = felt but not disruptive
6 = felt and caused some distress
8 = felt and caused significant discomfort
10 = totally unacceptable

Profile Name	Gz	Gx	Peak Alpha (rad/s^2)	Cab Displacement (degrees)	Transition Time (sec)
A	1	0.5	10	26.57	0.68
B	1	0.5	7	26.57	0.81
C	1	0.5	4	26.57	1.07
V	1	0.5	2	26.57	1.51
D	1.4	0.5	10	19.47	0.58
E	1.4	0.5	7	19.47	0.69
F	1.4	0.5	4	19.47	0.92
W	1.4	0.5	2	19.47	1.30
G	2	0.5	10	14.04	0.49
H	2	0.5	7	14.04	0.59
I	2	0.5	4	14.04	0.78
J	2	1	10	26.57	0.68
k	2	1	7	26.57	0.81
l	2	1	4	26.57	1.07
x	2	0.5	2	14.04	1.10
m	4	0.5	4	7.13	0.55
n	4	1	4	14.04	0.78
o	4	1.5	4	20.56	0.94
y	4	0.5	1	7.13	1.11
z	4	1.5	1	20.56	1.88
p	6	0.5	4	4.76	0.45
q	6	1	4	9.46	0.64
r	6	1.5	4	14.04	0.78
s	8	0.5	4	3.58	0.39
t	8	1	4	7.13	0.55
u	8	1.5	4	10.62	0.68

Table 1. Conditions for each of 26 profiles.

Results

Pitch Results- The 26 profiles were analyzed in 4 comparisons in which one of the factors (Gz or Gx) was fixed at one level so that an analysis could be performed for the other 2 factors. The dependent variable was the mean rating (ARR) across the 3 repetitions for each subject and profile. Repeated measures analyses of variance were performed using subject interactions as error terms. These four analyses are represented in Figures 3-6 and show the relationships among the three conditions of Gz, Gx, and alpha. Figure 3 shows that the ARR was not affected by alpha, as long as Gx was low. Figure 4 shows that ARR was unaffected by alpha magnitude but increased with increased Gx when Gz was low. In other words, it was the Gx that bothered subjects, not the rate of the pitching motions. Figure 5 shows that ARR is a function of both linear components, but in opposite directions, showing more sensitivity when in high Gx and less sensitivity when in high Gz. Figure 6 shows that even at a moderate Gz level, ARR is not sensitive to alpha, but still shows response to the Gx component. These results suggest that high angular artifacts need not be a serious concern in DFS design. All rates from 1 to 10 radians/ sec^2 were rated nearly the same subjectively, regardless of the G level attained. Subjects showed considerably more sensitivity to increasing Gx bias than to increasing angular acceleration spikes, and high Gz somewhat masks both effects. A summary of the results is contained in Table 2. Though not statistically significant, there was a trend for faster alpha to be preferred at lower Gz levels.

Roll Results - Methods of experimental design and analysis were identical to the Gx portion of the experiment. Table 3 shows the results for the lateral artifacts. The trend for faster alpha to be preferred at lower Gz levels was not observed in the roll artifacts.

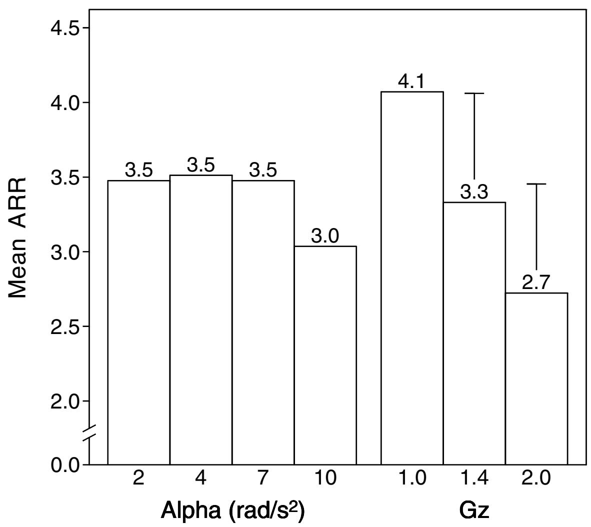

Figure 3. Main effect means. Gx=0.5. Whiskers are minimum significant difference from the Bonferroni paired comparison procedure.

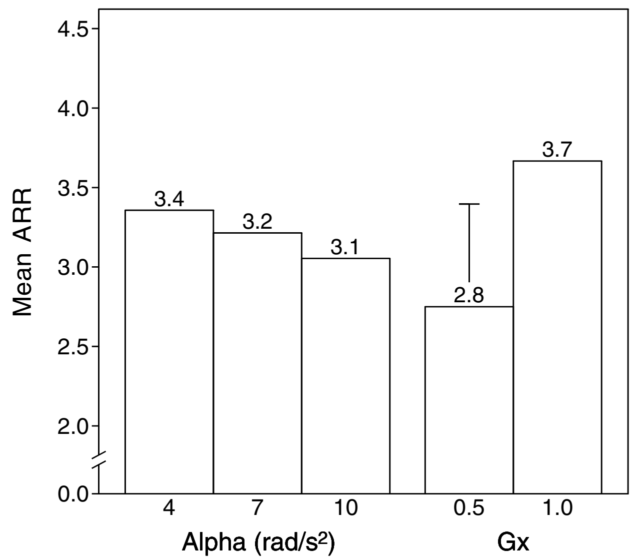

Figure 4. Main effect means. Gz=2.

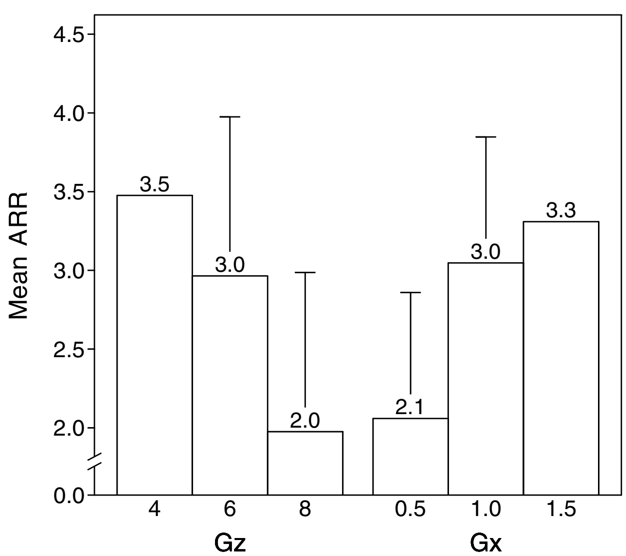

Figure 5. Main effect means. Alpha=4.

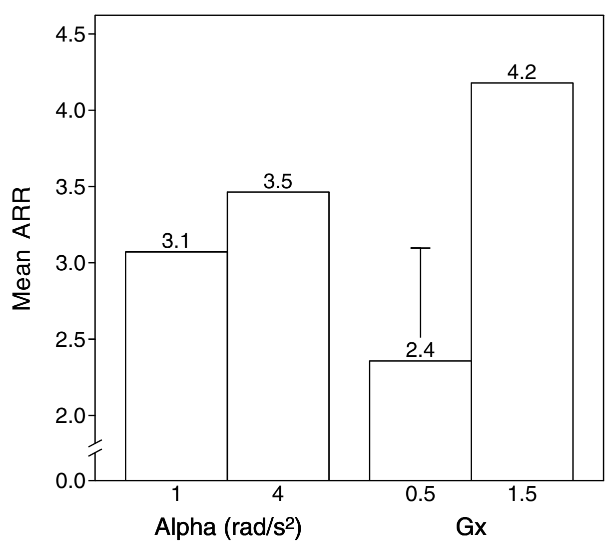

Figure 6. Main effect means. Gz=4.

Increase in the following Factor	Effect on Discomfort
Alpha	None
Gz	Decrease
Gx	Increase

Table 2. General findings of the Pitch analysis

Increase in the following Factor	Effect on Discomfort
Alpha	None
Gz	Decrease
Gy	Increase

Table 3. General findings of the Roll analysis

Test Summary- It was anticipated that very high alphas, such as 10 radians per second squared, would be deeply disturbing and possibly biodynamically dangerous. However, this was not at all the finding. The results indicate the effect of these artifacts to be no more than a mild disturbance over the expected range of G loading and artifact magnitudes. The tests also suggest that, for the range of accelerations tested, precision in Gx and Gy, as G magnitude increases, is more important than is precision in angular acceleration. Specific results of the tests are:

- Subjects preferred lower Gx and Gy to higher ones significantly.
- High angular accelerations (alphas) were slightly preferred to low alphas, but all alphas were comfortable, an unexpected result.
- Quicker transitions were preferred, especially at low Gz. At high Gz, the Gz seemed to mask this effect.

Conclusion

There appears to be no biodynamic reason to preclude the application of high fidelity, rapid acting, high torque gimbals to enable close matching of the rectilinear requirements. A centrifuge occupant will not be any more disrupted by the high angular acceleration artifacts associated with rapid response than they are by today's slower machines.

Credits

This work has been accomplished collaboratively under Cooperative Research and Development Agreements (CRDA) 96-AFIT-02 between Environmental Tectonics Corporation (ETC) and the Air Force Institute of Technology, and CRDA 99-141HE-01 between ETC and the Human Effectiveness Directorate of the Air Force Research Laboratory.

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Visual and Vestibular Determinants of Perceived Eye-Level

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Summary

Both gravitational and optical sources of stimulation combine to determine the perceived elevations of visual targets. The ways in which these sources of stimulation combine with one another in operational aeronautical environments are critical for pilots to make accurate judgments of the relative altitudes of other aircraft and of their own altitude relative to the terrain. In a recent study (Cohen, Stoper, Welch, & DeRoshia, 2001), my colleagues and I required eighteen observers to set visual targets at their apparent horizon while they experienced various levels of G_Z in the human centrifuge at NASA-Ames Research Center. The targets were viewed in darkness and also against specific background optical arrays that were oriented at various angles with respect to the vertical; target settings were lowered as G_Z was increased; this effect was reduced when the background optical array was visible. Also, target settings were displaced in the direction that the background optical array was pitched. Our results were attributed to the combined influences of otolith-oculomotor mechanisms that underlie the elevator illusion and visual-oculomotor mechanisms (optostatic responses) that underlie the perceptual effects of viewing pitched optical arrays that comprise the background. In this paper, I present a mathematical model that describes the independent and combined effects of *G_Z intensity* and the *orientation* and *structure* of background optical arrays; the model predicts quantitative deviations from normal accurate perceptions of target localization under a variety of conditions. Our earlier experimental results and the mathematical model are described in some detail, and the effects of viewing specific optical arrays under various gravitational-inertial conditions encountered in aeronautical environments are discussed.

Introduction

The perceived locations of visual targets depend on both retinal and extra-retinal sources of information (Bell, 1823; Helmholtz, 1866; Hering, 1879; Wade, 1978). The retinal information is derived from the images of the targets on the retina, their locations on the retina, and the shapes, locations, and orientations of images from other objects in the visual field, particularly those that comprise the background optical array against which the target objects are viewed. The extra-retinal information is derived from the position of the eyes relative to the head, and of the head relative to a specific external frame of reference, such as that provided by gravity. When the relationship between an observer and the gravitational frame of reference is altered, as when the observer is tilted with respect to gravity, or when the magnitude or direction of the gravitational-inertial force (GIF) is altered, as often occurs in accelerating aircraft or spacecraft, the apparent locations of seen objects are usually altered as well.

Two illusions, the oculogravic illusion and the elevator illusion are extremely common (and often go unrecognized) in operational aviation environments. These illusions cause errors in the perceived locations of visual targets that are viewed by observers in accelerating vehicles (Cohen, 1973; Cohen, Crosbie, & Blackburn, 1973; Graybiel, 1952; Schöne, 1963; Whiteside, Graybiel & Niven, 1965). The oculogravic illusion results when an observer is exposed to a change in both the direction and the magnitude of the GIF acting on his/her body, as when an airplane is accelerating, decelerating, or is in an uncoordinated turn. In this illusion, the observer experiences not only a change in the apparent location of isolated visual targets, but a change in the apparent orientation of the surrounding visual array as well. In contrast, the elevator illusion results when an observer is exposed to a change in the magnitude, but *not* the direction, of the GIF, as can occur in parabolic flight or in a coordinated turn. In this illusion, an isolated visual target appears to be above its true location when viewed in hypergravity (where the illusion is also often referred to as the *G-excess effect*), and below its true location when viewed in hypogravity (where the illusion has been called the *oculo-agravic illusion*). The elevator illusion is greatly attenuated when the target is viewed in the presence of a structured visual array (DiZio, Li, Lackner & Matin, 1997; Schöne, 1963), but specific quantitative data regarding the amount of attenuation as a function of optical structure had not been reported until just last year (Cohen et al., 2001). The

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elevator illusion has been attributed to changes in oculomotor control that result from atypical stimulation of the otolith organs under altered gravitational-inertial conditions (Cohen, 1973; 1992; 1996).

Altered gravitational-inertial conditions are not the only means by which changes in the apparent locations of visual targets can be brought about; changes in the orientation of the visual background against which a target is viewed can have similar effects. When a background optical array is not aligned with the observer's body, for example when the array is pitched, i.e., rotated up or down about an observer's left-right body axis, it can produce dramatic illusory changes in the apparent elevation, or height, of a visual target. The array can be comprised of a small box (Cohen, Ebenholtz & Linder, 1995; Kleinhans, 1970; Stoper & Cohen, 1989; 1991), an entire room (Cohen et al., 1995; Matin & Fox, 1989), or even individual tilted lines (DiZio et al., 1997; Matin & Li, 1992; 1994). In the aviation setting, these effects can result from viewing sloping terrain or banks of clouds.

Clearly, these illusions can lead to disorientation in flight when pilots do not attend to their instruments and rely instead on physiological stimulation provided by their visual and vestibular systems. The current paper represents a first-order attempt to model the effects of altered visual and vestibular stimulation as they affect the spatial localization of simple visual targets. This particular modeling attempt is restricted to acceleration conditions in which the magnitude, but not the direction, of the GIF is altered (i.e., conditions that lead to the elevator illusion rather than oculogravic illusion).

In the study by Cohen et al. (2001), we evaluated the relative contributions of retinal and extra-retinal information on localizing a visual target by systematically altering: 1) the orientation of the optical array, 2) the structure of the array, and 3) the intensity of the GIF. Observers were exposed to various combinations of these variables while they adjusted the position of a target so that it appeared to be at their horizon. The data from this study provide the basis for the model reported here.

Description of the Study

Observers - Eighteen observers signed a document indicating informed consent, were screened for tolerance to acceleration on the centrifuge by demonstrating their ability to undergo more than five minutes of continuous exposure to 2.0 G_Z without performing any straining maneuvers and without experiencing any difficulties, and were determined to have 20/30 vision or better, either uncorrected or as corrected by eyeglasses or contact lenses.

Apparatus - Each observer was seated on a freely swinging chair that faced radially outward in the darkened gondola of the human-rated centrifuge at Ames Research Center. The chair was individually balanced for each observer to assure that the GIF was increased exclusively along the **z** (head to foot) body axis, as verified by a tri-axial accelerometer mounted on the chair at the level of the observer's ears.

A tightly fitting helmet, rigidly attached to the chair, stabilized the position of the observer's head so that the eyes were centered with respect to an adjustable box (background array) that could be pitched towards or away from the observer by $\pm 20^{o}$. The interior of the box was covered on all surfaces with 10-to-the-inch graph paper that was aligned with the edges of the box, and the box was fitted with eight electro-luminescent strips that defined the eight interior edges. Thus, the illuminated edges were the four that defined the rectangular distal surface, and the four that protruded from the corners of this surface towards the observer along the outer edges of the floor and the ceiling of the box; the four edges closest to the observer at the open end of the box were not illuminated. The electro-luminescent strips provided the sole source of illumination to the box.

When viewed at the rear of the box, the vertical electro-luminescent lines subtended about 45^{o} visual angle from top to bottom, and were laterally separated by approximately 31^{o}. A light-emitting diode (LED) was mounted in a track that ran from the top to the bottom of the box along the center of its rear wall. An electric motor controlled the vertical position of the LED in its track, and another motor adjusted the pitch orientation of the box.

Experimental Design - The experiment consisted of 27 test conditions that were derived by combining three conditions of optical structure with three orientations of the box and three intensities of GIF. The conditions were: _Optical structure_ - 1) the box was brightly illuminated, and all interior details, as well as the LED target, were fully visible, 2) the box was dimly illuminated by the electro-luminescent strips that defined its interior edges; the observers reported that only the strips and the LED target were visible, and 3) the box was dark, except for illumination of the LED target itself. _Orientation_ - l) the box was pitched up 20^{o} (i.e., top towards observer), 2) the box was level, and 3) the box was pitched down 20^{o}. _GIF_ - 1) the centrifuge provided 1.003 G_Z (nominally, 1.0 G_Z), 2) the centrifuge provided 1.5 G_Z, and 3) the centrifuge provided 2.0 G_Z at the observer's head.

The experimental conditions of optical structure and orientation were counterbalanced across observers, and the sequence of GIFs within each session was determined by a Latin-square design.

Data Collection - Experimental data were fed from the centrifuge gondola via slip-rings to a digital computer, and data collection was initiated no sooner than one minute after the centrifuge had achieved the desired steady-state G_Z. The experimenter set the target near the top or bottom of the box on alternating trials, and the observers adjusted the position of the target until it appeared to be at their horizon; the observers then pressed a button, and the location of the target was automatically registered. The experimenter repositioned the target, and the observers again attempted to place it at their horizon. The experimenter set the box at a new orientation, and the procedure was repeated until four settings to apparent eye level were obtained from each observer at each of the three box orientations. All viewing was binocular. Whenever the experimenter adjusted the position of the target or the orientation of the box, the observers closed their eyes.

Summary of Results - As verified by ANOVA and regression analyses, the settings of the target were progressively lowered as the magnitude of the GIF was increased. Thus, a target that remained at true eye level would appear to be progressively more elevated with increased G_Z. Similarly, the settings of the target varied with the orientation of the background optical array (box) in which the target was viewed; the settings were biased in the same direction as that in which the array was pitched. Thus, a target at true eye level would appear to be higher when the array was pitched down, and lower when the array was pitched up. The optical structure of the array also influenced settings of the target. Overall, the settings made in the dark tended to be lower (because the effects of increased G_Z were not attenuated) than those made either when the dimly illuminated electro-luminescent strips or the fully illuminated box defined the background array (where the effects of increased G_Z were attenuated). The effects of optical structure significantly interacted with both the effects of G_Z and those of array orientation. Thus, optical structure was shown to have two independent qualities: 1) it allows a tilted visual array to bias perception in the same direction as the array is pitched, and 2) it inhibits a change in the strength of the GIF from biasing perception. The data of this study are depicted in Figure #1.

Development of the Current Model

Variables

The study described above (Cohen et al., 2001) provides a clear picture of the critical stimuli, and the likely mechanisms that subserve the perception of target elevation. Three distinct underlying variables emerge from that study:

Variable 1 – The data illustrate a general effect of the intensity of the GIF on the perceived elevation of the target. This effect occurred both in the dark and with all of the background optical arrays used in the study. Based on the data shown in Figure #1, this effect is a linear function of the intensity of the GIF under each of the conditions tested, although the slope of the function differs for the different arrays. In previous studies (e.g., Cohen, 1973), this effect was termed the "elevator illusion," and its underlying mechanism is considered to be a change in stimulation of the otolith organs, resulting in an otolith-oculomotor drive that changes the registered position of the eyes in the head (Cohen, 1996).

Variable 2 – The data indicate an effect of the orientation of the optical array on the perceived elevation of the target. This effect occurred whenever the background optical array was visible, but because it was extremely small in the dark (only 0.04^{o}/degree), and was virtually constant in the light ($.45^{o}$ to $.46^{o}$/degree) at all levels of GIF tested, it was shown to depend only on the structure and the orientation of the optical array, but to be independent of the GIF. In previous studies (e.g., Cohen et al., 1995; Stoper & Cohen, 1989; 1991; Matin & Fox, 1989; Matin & Li, 1992), this effect was referred to as "visual capture," and it is considered to be due to an optostatic drive that independently changes the registered position of the eyes in the head (Crone, 1975; Cohen et al., 1995).

Variable 3 – Because the effects of increased GIF depended on the structure of the background visual array, the data suggest a separate retinal mechanism to suppress the otolith-oculomotor drive in the presence of such an array. (As was shown, with a dark background, the apparent elevation of the target changed at a mean rate of 9.41^{o} per G_Z; when the array was comprised of dimly lit electro-luminescent strips, which provided additional optical structure, this effect was reduced to 4.44^{o} per G_Z, a reduction of 53%; when the array was a fully illuminated box, providing rich optical structure, the effect measured 3.30^{o} per G_Z, a reduction of 65%.) The otolith-oculomotor drive to be suppressed by the retinal structure of the array varies with the intensity of the GIF. Thus, attenuation of the otolith-oculomotor drive is jointly affected by the intensity of the GIF and by the structure of the optical array.

Combined Action of Variables

A simple multiple regression analyses of the data from Cohen et al. (2001) was used to generate the linear model presented here. The regression analysis suggests four separate parameters that combine to account for the individual and interactive effects of visual and vestibular stimulation in the localization of visual targets. These parameters are:

A. A **fixed constant** that is given by idiosyncratic factors determined by the individual subjects, and specific viewing conditions. This constant provides the zero intercept for the model, and indicates where a target would be positioned when all of the other parameters are reduced to zero, i.e., when a target is viewed in the absence of gravity and in the absence of any background optical array. This constant, designated as ***b*** in the current model, indicates that the perceived elevation of a single target viewed in the dark and in the absence of gravity would be 4.36^{o} below the objective level of the eyes.

B. An **otolith-oculomotor drive** that is caused by altered stimulation of the otolith organs as a result of exposure to increased GIFs; the values for this variable are directly proportional to the intensity of the GIF acting on the observer. This term is given by α * (*g*), where α is a proportionality constant that reflects the effectiveness of otolith organ stimulation, and *g* is the intensity of the GIF in units of G_Z. For a single target viewed in an otherwise totally dark environment, this parameter causes the target to appear progressively more elevated at a rate of 7.67^{o} for every 1.0 G_Z increment.

C. A **retinal-oculomotor drive** that is given by the orientation of the background optical array, weighted by the amount of optical structure in the array. The best estimate for the weighting of this mechanism is given by the empirically determined slope of the change in target settings relative to the change in orientation of the optical array. This term is given by β * (*o x os*), where β is a proportionality constant that reflects the relative amount by which the oculomotor drive is activated by the product of *orientation x optical structure*. For the target in the dark, the background pitch orientation values of –20^{o}, 0^{o} and +20^{o} are multiplied by the empirically-determined slope of .04^{o} per degree; for those conditions where the background optical array was visible, the pitch orientation values of –20^{o}, 0^{o} and +20^{o} are multiplied by the empirically-determined slope of .46^{o} per degree. These products are then incorporated into the multiple linear regression model, which yields a value of 0.99 for the β coefficient.

D. A **Retinal suppression of the otolith-oculomotor drive**, which results from the property of optical structure in the background array to suppress the effects of the GIF. Since the amount of suppression differs with both the intensity of the GIF and the optical structure of the background array, this parameter is given by γ* (*g x sp*), where γ is a proportionality constant, *g* is the intensity of the GIF applied along the z axis, and *sp* is the relative ability of the background array to suppress the effects of the GIF. As empirically determined, this parameter takes on the values of 0 (i.e., no suppression) for an unstructured optical array (in the dark), .53 suppression with the background dimly illuminated, and .65 suppression with the full grid visible. Since the stimulus to be suppressed is directly proportional to the intensity of the GIF, the values for this parameter are 0 at all levels of G_Z in the dark, .53, .795, and 1.06 at 1.0, 1.5 and 2.0 G_Z, respectively, with the background array comprised of strips, and .65, .975, and 1.3 at 1.0, 1.5 and 2.0 G_Z, respectively, with the full optical array. The value of the constant, γ, is 4.97.

Thus, as shown in Table #1, the complete model is summarized as follows:

$$\text{Target Setting} = \alpha *(g) + \beta *(o \times os) + \gamma *(g \times sp) + b$$

Where: α *(*g*) represents the effects of the otolith-oculomotor drive due to changes of the GIF; β *(*o x os*) specifies the retinal-oculomotor drive, due to the orientation and optical structure of the background; γ *(*g x sp*) designates the suppression of the otolith-oculomotor drive, which depends on the structure of the optical array and the intensity of the GIF, and *b* represents the zero intercept that would result in the absence of both gravity and background optical structure. A plot of the empirical data from the study (Cohen et al., 2001), compared with those generated by the model, is shown in Figure #2. Although the present model accounts for the experimental data extremely well, applying these modeling effects to more operationally realistic settings is probably quite a different matter.

Limitations of the Current Model

The model presented here is obviously limited to those conditions where the GIF is systematically manipulated in magnitude alone, and where its direction is unchanged; also the specification of the background optical array is highly restricted in the experimental study from which the model is derived. Clearly, the current model reflects a work in process. Nevertheless, the model constitutes a starting point from which additional variables can be explored. The addition of terms for somesthetic components and for dealing with changes in the direction as well as the magnitude of altered GIFs are conceptually feasible, and extended modeling efforts regarding spatial orientation under a wide range of more operationally realistic conditions can ultimately be accomplished. As long as disorientation in flight remains an operational problem, any attempts to extend our understanding of these issues are probably quite worthwhile.

Unfortunately, the expansion and further application of the model to more operationally realistic settings must await future investigations.

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Figure #1

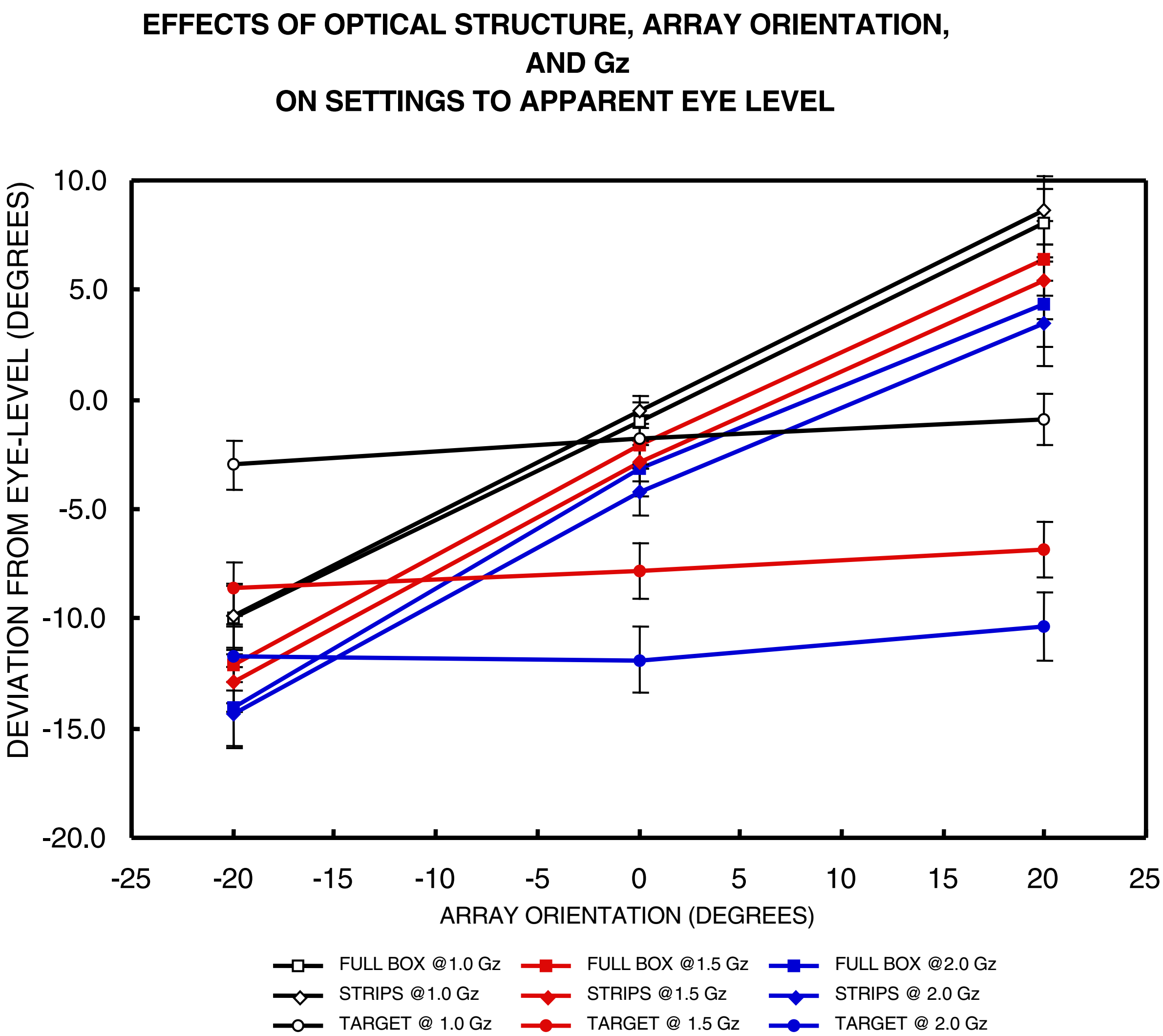

EFFECTS OF OPTICAL STRUCTURE, ARRAY ORIENTATION, AND Gz ON SETTINGS TO APPARENT EYE LEVEL
DEVIATION FROM EYE-LEVEL (DEGREES)
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25
-20
-15
-10
-5
0
5
10
15
20
25
ARRAY ORIENTATION (DEGREES)
FULL BOX @1.0 Gz
STRIPS @1.0 Gz
TARGET @ 1.0 Gz
FULL BOX @1.5 Gz
STRIPS @1.5 Gz
TARGET @ 1.5 Gz
FULL BOX @2.0 Gz
STRIPS @ 2.0 Gz
TARGET @ 2.0 Gz

Table #1

SUMMARY OUTPUT OF FULL REGRESSION ANALYSIS OF MODEL RESULTS

$$Target\ Setting = \alpha * (g) + \beta * (o\ x\ os) + \gamma * (g\ x\ sp) + b$$

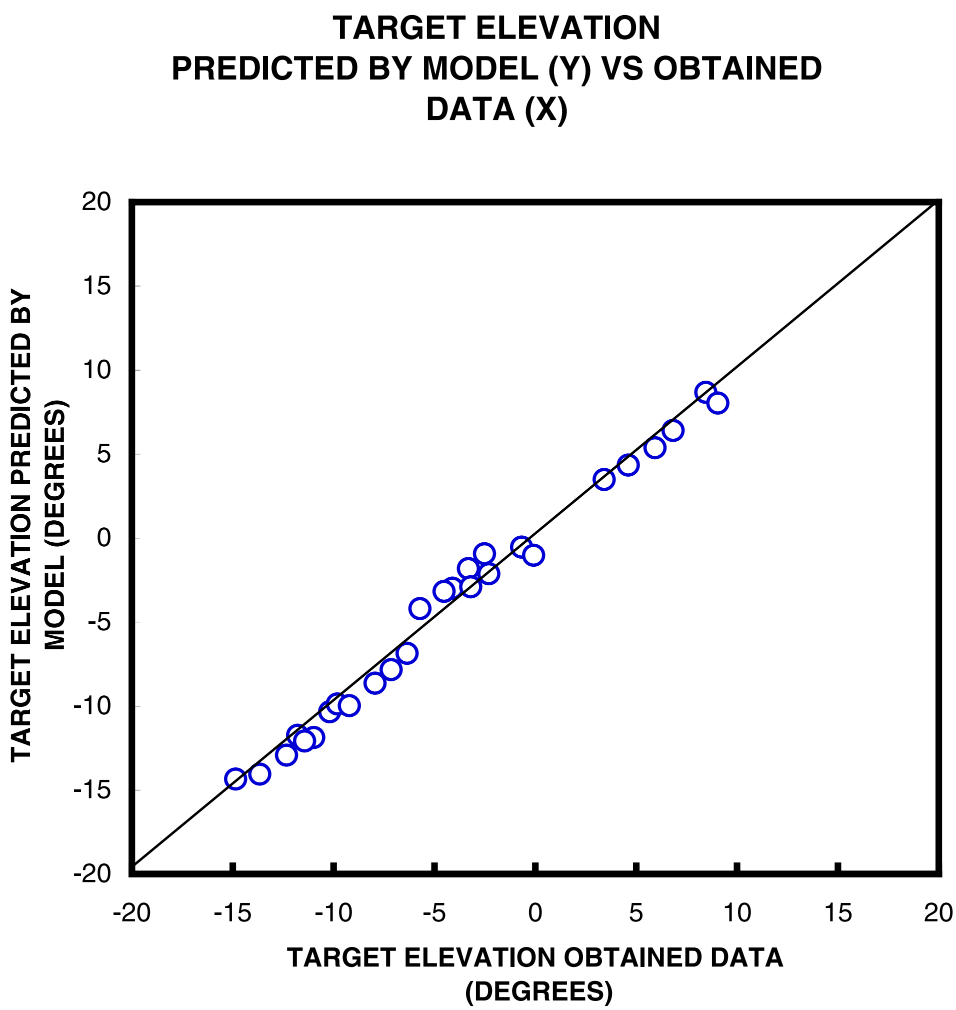
Regression Statistics	
Multiple R	0.994
R^2	0.987
Adjusted R^2	0.986
Standard Error	0.849
Observations	27

ANOVA

	df	SS	MS	F	Significance F
Regression	3	1280.36	426.79	592.14	6.61E-22
Residual	23	16.58	0.72		
Total	26	1296.94			

Model Parameter	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	4.36	0.62	7.00	3.88E-07	3.07	5.64
Otolith-Oculomotor Drive	-7.67	0.43	-18.00	4.73E-15	-8.55	-6.79
Retinal-Oculomotor Drive	0.99	0.03	37.34	4.35E-22	0.94	1.05
Retinal Suppression of Otolith-Oculomotor Drive	4.97	0.37	13.35	2.55E-12	4.20	5.74

Figure #2


TARGET ELEVATION
PREDICTED BY MODEL (Y) VS OBTAINED
DATA (X)
TARGET ELEVATION PREDICTED BY
MODEL (DEGREES)
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0
5
10
15
20
TARGET ELEVATION OBTAINED DATA
(DEGREES)

Reducing Negative Effects from Virtual Environments: Implications for Just-In-Time Training

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Summary

Current U.S. Naval doctrine places increasing emphasis on providing just-in-time training. This means training the deployed sailor when they need the training, wherever they happen to be. This differs from classic training doctrine that calls for placing a completely trained expert in the field. This shift in doctrine is a direct response to reduction in force sizes, necessitating fewer experts and more generalists. Just-in-time training requires the generalists to be somehow brought up to expert standard in the field. One way to fill this requirement is through the use of deployable training systems. In this sense, 'deployable' refers to a system that requires minimal space, demands little if any maintenance, and is easy to set-up. Virtual Environment (VE) training systems, with their inherently small footprint, and fundamental reliance on software rather than hardware solutions, represent a seemingly elegant solution to many of these challenges. However, VE systems bring with them their own unique set of challenges that can negatively impact skill learning during VE exposure, as well as significantly reduce military personnel's ability to perform mission-critical tasks following VE exposure.

For instance, a group of side effects collectively known as cybersickness can be especially debilitating to users during VE training. Symptoms range from the distracting, such as eyestrain and blurred vision, to the performance detracting, such as visual motor coordination and balance disturbances. Cybersickness occurs in approximately 80-95% of individuals receiving virtual training, with up to 30% of the trainees opting to terminate training before completing it. VE exposure can also produce aftereffects such as eyestrain, dizziness, and nausea, that can last more than an hour after a training session, and in about 8% of individuals symptoms can last for more than six hours post session. Prolonged exposure to VEs can lead to distinct physiological changes, such as changes in the resting point of accommodation or even recalibration of perception-action couplings following exposure to visual scenes. These issues become even more critical when using VE systems to deliver deployable, just-in-time training. When these simulations are placed aboard ship, the physical ship motion will be completely uncorrelated to the motion being visually represented in the VE. This discordance will most certainly exacerbate any already existing side/after effects. The net result of these effects is an increased likelihood of users receiving less-than-adequate training *during* VE exposure, and being unfit to perform their duties *following* VE exposure.

It is precisely these compounded effects that current research efforts seek to quantify and to reduce. To this end, two parallel approaches have been pursued. In the first, participants 'flew' a personal computer-based flight simulator in the absence of any physical motion, were exposed to actual ship motion in the absence of any simulator exposure, and flew the flight simulator while deployed aboard a small ship. Results from this

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study indicate that even when benign ship motion and benign flight simulated motion are combined, a physiological degradation can occur. The effects of the uncoupled motion appear additive in nature, but do not cause emergent effects greater than the sum of the individual motions. A second effort, currently in progress, explores the notion of subtracting the physical motion from the visually displayed motion to reduce these negative additive effects. Additional engineering and behavioral studies are planned.

Introduction

Simulation Sickness

It is not known why individuals get sick when exposed to a flight simulator. It has been suggested that flight simulators create a perceptual conflict that results in sickness (Reason and Brand, 1975; Kennedy and Frank, 1985; Kennedy, Berbaum and Lilienthal, 1992). For example, if an individual is flying a visual-only flight simulator, he might perceive that he is moving forward based on the information that the brain is receiving from the visual system. However, his brain would simultaneously receive information from his vestibular and proprioceptive (muscle) systems that correctly identify that in reality he is sitting still. The conflict between information produced by perceptual systems immersed in the simulation and those fixed in reality can produce motion adaptation syndrome (MAS). MAS is a collection of symptoms and side-effects that occur when a human is placed into a novel real or apparent motion environment and tries to maintain spatial orientation and motor coordination within the novel environment.

The majority of simulation-based training in the Navy focuses on the aviation domain. From the Navy's perspective, about one in four pilots report symptoms that last more than an hour after a flight simulation training session, and about 8% report symptoms lasting for more than six hours (Baltzley, et al. 1989). The typical symptoms reported are eyestrain, fatigue, drowsiness, sweating, headache, and difficulty concentrating (Lawson, Graeber, Mead, and Muth, 2002). Moreover, it has been found that exposure to flight simulation can cause measurable changes in motor performance, as 1.5% of pilots report difficulty flying an actual aircraft following exposure to a flight simulator (Ungs, 1989). Approximately 4.6% of trainees develop long-term aftereffects, including balance problems, deficits in eye-hand coordination, persistent difficulty in concentrating and sleeping, and "simulator flashbacks", including visual flashbacks or distortions and continued sense of detachment from reality (Ungs, 1989). These data were generated on land-based simulators and represent a significant source of performance degrading side effects for individuals exposed to these simulators

Sea sickness

At the same time, it has long been known that exposure to ship-like motion can result in sickness. Considerable attention has been placed on the problem since the events of World War II demonstrated the need to move large numbers of troops by sea and the consequential impact of seasickness (Morales, 1949; Bruner, 1955). Early work concluded that linear translations contribute significantly to seasickness (Tyler and Bard, 1947). Later work found that vertical translational oscillation was an accurate predictor of sickness (Lawther and Griffin, 1987). The culmination of years of work regarding provocative ship motion is summarized in MIL-STD-1472C (Figure 43, page 176). This document reveals that vertical oscillation (heave motion) at a frequency between 0.16 and 0.2 Hz (10-12 cycles per minute) tends to provoke seasickness. Lawther and Griffin (1987) present a wider range of provocative frequencies, pointing out that humans are most affected by vertical oscillations in the frequency range of 0.1 to 0.5 Hz (6-30 cycles per minute). Although heave ship motion data do not explain the underlying physiological mechanism of seasickness, they do point to a causal motion factor: how quickly individuals get sick will depend on a combination of the frequency and acceleration characteristics of the heave motion. As with simulator-based sickness, seasickness results in significant decreases in crew readiness.

Combined effects of virtual and physical motion: Decoupled motion environments

Studies of aircrew and flight navigators suggest that they are more susceptible to airsickness than pilots (Royal, Jessen and Wilkens, 1984; Strongin and Charlton, 1991). A study of operators within a Command and Control Vehicle (an armored tracked vehicle containing four workstations within an enclosed crew compartment having no outside view), found worse crew performance and increased motion sickness when operators had to attend to computer screens while the vehicle was moving (Cowings, Toscano, DeRoshia and Tauson, 1999). The performance decrements were attributed to visual fixation during vehicle motion, since visual fixation during the stationary conditions did not produce the decrements. This finding agrees with an earlier report that video displays alone do not disturb operators (Smith, Cohen and Lambert, 1981).

Thus, it is probable that the decoupling between physically experienced motion and visual scene motion may lead to sickness, and perhaps, other negative effects. Nevertheless, despite the trend towards placing training simulations which provide a visually indicated motion stimulus, aboard ships which provide a completely distinct physically indicated motion stimulus, there has been no concerted effort into quantifying the causative relationship between decoupled motion environments and negative effects. This paper reports two research efforts that aim to fill this knowledge gap. The first explores the negative effects of training in a minimally provocative Virtual Environment flight simulation placed aboard a ship with minimally provocative motion. The second focuses on identifying methods for reducing negative effects.

Experiment 1: Minimally provocative simulation, minimally provocative ship motion

Twenty-six males ranging from 33-45 years of age participated in the study, the majority of whom had some form of flight experience. All participants completed a Pre-test and Post-test in a mobile field laboratory (a parked trailer fully equipped as a laboratory and climate-controlled). During each test period, participants had their balance and dynamic visual acuity tested, and symptoms assessed. Between the Pre-test and Post-test, one of three experimental manipulations (independent variable) occurred. Participants either piloted a flight simulator while riding aboard a Yard Patrol (YP) boat (ship + flight sim), rode aboard a YP boat without piloting the flight simulator (ship) or piloted the flight simulator on land (flight sim). Participants completed one condition per day.

During the Pre and Post testing periods three measures were recorded: *Balance*, quantified using the Neurocom Balance Master; *Dynamic Visual Acuity*, quantified by having participants read a visual acuity chart while making yaw-axis head movements; and *Symptom Assessment*, using the Nausea Profile (Muth, Stern, Thayer and Koch, 1996) and the Simulator Sickness Questionnaire (Kennedy, Lane, Berbaum and Lilienthal, 1993).

During the flight sim condition participants used a CRT based simulation (no motion platform) to perform a basic ‘follow me’ trajectory using joystick and throttle controls. Participants performed this maneuver for one hour. During the ship and ship+flight sim condition, the YP completed 2 clockwise octagons, with one octagon covered in approximately 30 min and each leg of the octagon lasting approximately 3.5 min. Ship speed was held as close to 6 kts as possible and 45^o course changes were made at full rudder (20^o), taking approximately 15 sec to make a course change. Participants were either exposed to a one-hour flight simulation (sim) or listened while seated and blindfolded, to a portion of a book on tape (ship). After ship exposure, participants were wheeled to the mobile field laboratory in wheelchairs to minimize re-adaptation to land due to walking. Ship motion was monitored and recorded using a 6-degree of freedom accelerometer package. The only significant motion recorded by the accelerometer was the roll of the ship during the full rudder (20^o) turns (Figure 1).

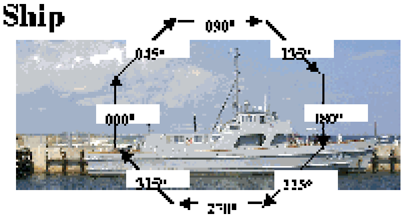
Pre-Test	Condition	Post-Test
• DVA • Balance • Q'airres	**Flight Sim** 	• DVA • Balance • Q'airres
Same	**Ship** 	*Same*
Same	**Ship + Flight Sim**	*Same*

Figure 1: Experiment 1 design. Regardless of condition (flight sim, ship, ship+flight sim), each participant received a Pre-test assessment prior to exposure to the condition and a Post-test assessment following exposure to the condition. The assessment included an evaluation of participants' balance, Dynamic Visual Acuity (DVA) and two questionnaire-based evaluations of sickness.

Due to scheduling logistics, the flight sim condition always occurred first (Day 1), followed by the other two conditions which were counterbalanced across the remaining two days. Thus, for each measure, it is not possible to directly demonstrate an effect of the flight sim condition. The results from the balance testing showed no significant differences between the ship and ship + flight sim conditions. By inference, it is highly likely that sim alone also did not affect balance. Similarly, the results from the symptom assessment were negligible for all conditions: the average nausea profile score was less than 4 out of 100 possible points, while the average simulation sickness questionnaire score was less than 3 out of 45 possible points.

Most interesting was the finding that dynamic visual acuity for the ship condition alone and for the flight sim condition alone each demonstrated a loss of approximately one-half line of acuity, while the ship + flight sim condition showed a summation effect, with a loss of one entire line (repeated measures ANOVA, p<. 05). These findings are all the more impressive in light of the findings of no significant difference in the other measurements –in particular, with regard to participants' own perception of their state of sickness. First, this suggests that combining dissimilar motion environments –decoupled motion environments- will, in fact, produce distinct negative effects. Second, this finding underscores the insidious nature of these negative effects- trainees can actually leave such an environment assuming themselves to be 'good to go' when in fact, they are in a state of decreased readiness. These results have significant implications for the method through which just in time training is delivered aboard ship, which will be addressed in Experiment 2.

Experiment 2: Methods for reducing sickness in decoupled motion environments

The results from Experiment 1 suggest that, alone, the two motion conditions under investigation do not produce sickness but, when combined, can in fact summate to produce a detectable effect. At first glance, this finding may seem preliminary. However, it is important to realize that the stimuli used were extremely minimal: the VE simulation utilized CRT technology, which is categorically different from the Head Mounted Displays that may be used aboard ship (Cohn, Mead, Giebenrath & Burns, 2002); the simulation was non-provocative, requiring users to follow a pre-set path rather than the more rapid scene changing that would be expected from a true flight simulation; and, finally, ship motion was negligible. Thus, these findings of significance are all the more indicative in light of their being identified in such a benign environment. In order to more completely flesh out the interactions between these two motion environments, a second experiment was performed, in which more provocative motion stimuli, both physical and virtual, were used.

O'Hanlon & McCauley (1974) have suggested that the most provocative type of motion occurs during vertical oscillation (corresponding to heave ship motion) at a frequency of 0.2Hz. A platform (Vertical Linear Oscillator, VLO, Brandeis University's Ashton Graybiel Spatial Orientation Laboratory) that supported this type of motion was developed, allowing for over 6 feet total vertical displacement. As well, a more immerssive simulation was integrated, using a Head Mounted Display unit, projecting a scene that would typically be encountered by a member of ship's crew. Finally, a device for coupling visual scene motion to physical motion was developed (Motion Coupling in Virtual Environments, MOCOVE).

Systematic observations are required to compare the side effects and aftereffects of an environment where both simulated ship motion and real ship motion exist and are not coupled to each other, that one may refer to as a "decoupled" virtual environment (VE). These effects can be quantified experimentally using the following environments:

- **VLO + uncoupled VE** – The uncoupled VE is a virtual environment in which no attempt has been made to correlate it with the motion of the VLO. The scene never changes elevation as the participants goes up and down
- **VLO + MOCOVE** – The MOCOVE device senses the motion of the VLO and couples this back into the VE. The visual perspective change in the VE is as similar as possible to what would occur if the participants were directly viewing the real surroundings.
- **VLO + natural coupling** – Here, the participants are not in a virtual environment. Instead, they have natural vision into the lighted laboratory, thus permitting them to see their environment with natural coupling to the motion of the VLO.

In all environments, a small set of experienced observers reported their motion sickness, disorientation and postural side effects and aftereffects.

Coupling was effected through the integration of a Motion Coupling in Virtual Environments (MOCOVE) prototype system. The current prototype MOCOVE system is capable of inertial tracking of the motion of a platform and updating the simulated visual perspective of an observer in a motion environment similar to what one would experience aboard a Naval ship (see Figure 2). This was demonstrated using the Naval Research Laboratory's (NRL) ship motion simulator (SMS) (Figure 3).

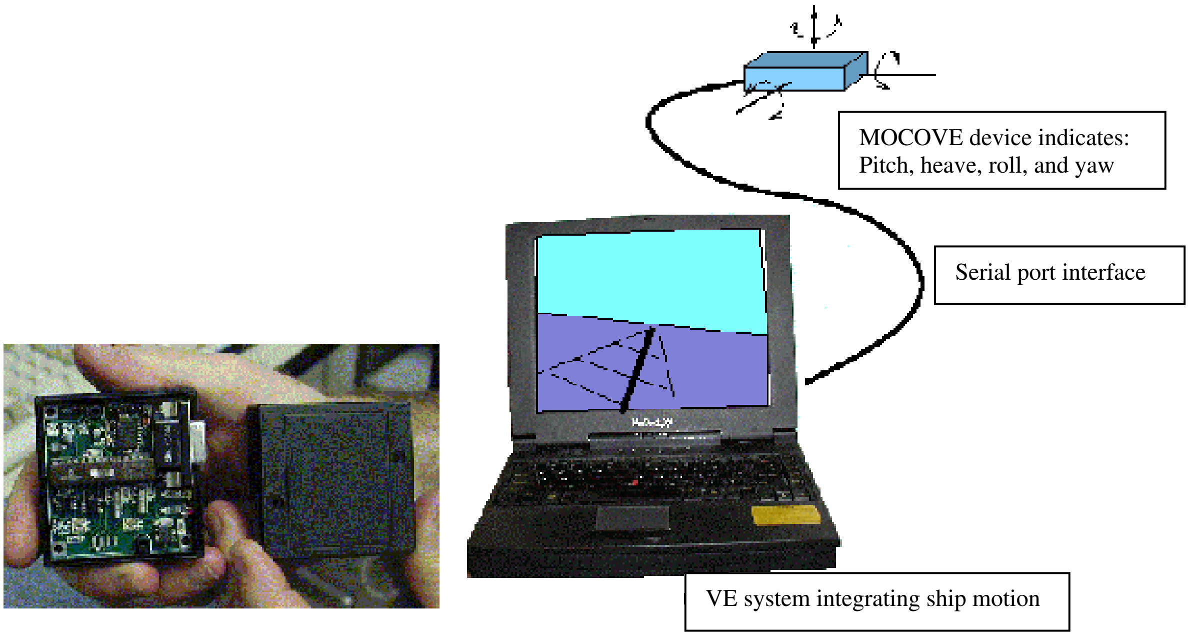


Figure 2: MOCOVE device. *Left:* The actual hardware. *Right:* Schematic for implementing MOCOVE. The device senses Pitch, Heave, Roll and Yaw motion and transmits this information, via serial interface, to a computer system. This information is integrated with the currently running simulation to produce an aggregate change in the visually presented scene that is coupled to the physical environment's motion.

Figure 3: Naval Research Laboratory's Ship Motion Simulator (SMS). Capable of +/- 14 degrees pitch; +/-5 degrees roll, 8 s period.

The MOCOVE system currently tracks three degrees of freedom (roll, pitch and heave), as follows. If the MOCOVE device is rotated about its axis to any position, the vector sum of 3 of its axes must be equal to 1 G pointing in the direction of the center of the earth. Accelerations from or to the earth's center modify this vector's magnitude by the appropriate acceleration. The vertical heave component is computed by integrating the acceleration over time. The shipboard environment is more complex – except at the ship's center of gravity, there are centrifugal forces involved. Due to low pitch and roll rates, these forces are negligible compared to those associated with heave and ignore them. Appendix A provides a portion of these calculations.

The basic experiment required six experienced observers to evaluate combinations of VLO and passive viewing of a scene with and without motion coupling, during 15-minute exposures. The VLO ran at 0.2 Hz, 1.9 m peak-to-peak amplitude. Participants reported that the natural environment produced the least amount of side effects, while the virtual environment coupled to the VLO via MOCOVE produced slightly more side effects. However, participants experienced a far greater level of side effects in the uncoupled VE case, that is, with

MOCOVE turned off. Thus, not only is the vestibular system itself a poor indicator of motion direction, but the visuo-vestibular system can be easily decoupled. At the same time, the above results indicate that this coupling can be re-introduced using basic VE techniques.

Conclusions

Experiment 1 examined a "best-case scenario" in which a minimally provocative ship motion stimulus was combined with a non-provocative flight simulator. It was expected that combining these minimal stimuli would cause MAS. In fact, although following the ship + flight sim condition participants reported negligible symptoms of nausea and simulator sickness and no balance disturbances were apparent, they could not see as well in a dynamic visual environment as they could prior to exposure to the flight simulator aboard ship. This finding is critically important, when two facts are considered. First, participants were exposed to a minimum stimulus. Second, in terms of decreased readiness, for instance with respect to pilots, loss of one line of dynamic visual acuity equates to the pilot missing their "wingman's" position, or the inability to discriminate a "bogie", when the pilot makes a quick head movement to scan their visual scene. This can be deadly in the highly dynamic environment of air combat maneuvers. Experiment 2 took these basic findings one step further, using more realistic stimuli. Again, the most provocative condition was one in which scene motion and physical motion were decoupled. Importantly, Experiment 2 demonstrated that by reintroducing this coupling, through the use of MOCVOE technology, the experienced sickness was reduced.

These results are of critical import in light of the recent, profound, changes in training doctrine occurring throughout the military. As U.S. forces continue to modernize and react to new threats, the most crucial changes involve delivering this training. Specifically, systems are being deployed with embedded training capabilities that may be used while the system itself is in motion. For example, virtual training systems are currently being developed for the specific purpose of placement aboard ships for use at sea. Land systems are being designed so that gunners may practice their art while their vehicle is underway and they are not otherwise engaged. The currently reported work demonstrates that an external and unrelated motion environment superimposed upon a virtual environment creates a level of side effects that are greater than the mere addition of the side effects one would experience from either environment alone. Given the great benefit ascribed to embedded training, a significant interfering factor such as this must be mitigated to the degree possible. Our current research efforts suggest one method achieving this.

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Appendix A: Equations for resolving G and Heave

Each accelerometer has 2 axes (x and y). We wish to compute the vector g. *Vx* and *Vy* are normalized readings from the X and Y-axes.

Solving for G

The readings *Vx* and *Vy* are the projections of *g* onto the *X* and *Y* vectors. *X* and *Y* are perpendicular.

$$V_x = \vec{g} \cdot \vec{x} = |\vec{g}||\vec{x}| \cos\phi \quad (1)$$

$$V_y = \vec{g} \cdot \vec{y} = |\vec{g}||\vec{y}| \cos(\phi + \frac{\pi}{2}) \quad (2)$$

$$|\vec{g}| = \frac{V_x}{|\vec{x}| \cos\phi} = \frac{V_y}{|\vec{y}| \cos(\phi + \frac{\pi}{2})} \quad (3)$$

Solving for the angle of G

We now solve for *g*'s angle, ϕ.

$$\frac{V_x}{\cos\phi} = \frac{V_y}{\sin\phi} \quad (4)$$

$$\frac{\cos\phi}{\sin\phi} = \frac{V_x}{V_y} \quad (5)$$

$$\phi = \tan^{-1}\frac{V_x}{V_y} \quad (6)$$

Solving for G magnitude

To avoid division by zero we select the appropriate relation. The units are based on the normalized values of *Vx* and *Vy*.

$$|\vec{g}| = \begin{cases} \frac{V_x}{\cos\phi} & \cos\phi \neq 0 \\ \frac{V_y}{\sin\phi} & \cos\phi = 0 \end{cases} \quad (7)$$

Solving for Heave

Integrate *g*'s vertical projection over the time step (currently dt = 1/4 s).

$$V_s = \int_0^t (|\vec{g}||\vec{y}| \sin\phi - 1)dt \quad (8)$$

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Exercise Induced Motion Intolerance: Role in Operational Environments

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Summary
Exercise induced motion intolerance is a newly recognized disorder. This condition has a profound impact on military individuals in operational environments. Individuals present with a variety of symptoms including: headache, nausea, vertigo, and disequilibrium, which occur after exercise. The symptoms generally worsen with time and can significantly impact patients' daily routines since, often, only minimal exertion produces symptoms. We present a cohort of fifteen patients with exercise-induced motion intolerance. We detail the diagnostic work-up in this group of individuals including differentiating this disorder from common motion sickness and other vestibular pathologies. All of the individuals responded to customized vestibular rehabilitation including vigorous physical exertion with head motion. Since this disorder is poorly recognized and responds well to treatment we hope to provide guidelines that will allow practitioners to manage this disorder. Information from this abstract has bearing involving mechanisms and predisposing factors involved in motion sickness for individuals in operational environments and on a variety of military vehicles.

Introduction

Exercise induced intolerance is a recently described balance disorder. There are sparse reports of conditions resembling this disorder in the literature.[1] No prevalence or gender specificity has been identified. The disorder is characterized by nausea and disequilbrium that occur with a change in head position during exercise. Patients will usually demonstrate difficulties performing sit-ups, push-ups, running, and swimming. However, these individuals do not have trouble riding a stationary bicycle.[2] Symptoms can continue or intensify post exercise and may require a cool down period before fully resolving. Patients are often affected by the emotional components of the disorder, which include the sudden onset of this disorder in previously healthy individuals and the subsequent fear of inability to perform occupational tasks in operational environments due to their symptoms. The disorder may be confused with motion sickness. However, these individuals rarely demonstrate classical motion sickness or variants such as Sopite syndrome. The

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etiology is poorly understood, but the disorder is an acquired phenomenon. Exercise induced motion intolerance must be distinguished from congenital anatomical inner ear malformations such as patent vestibular aqueduct which causes dizziness with exercise. The condition has military relevance as individuals with this disorder perform poorly in most operational settings and cannot perform physically demanding military tasks. In addition, the physical conditioning training required of active duty individuals cannot be performed if the service member suffers from exercise-induced motion intolerance. Finally, there may be a causal relationship between head trauma and this disorder.[2]

A number of therapeutic modalities have been attempted to control or treat this disorder.[3] Traditional vestibular rehabilitation has been unsuccessful in treating this disorder likely because the therapy fails to stress the system sufficiently. Virtual reality has also been tried but head on body motion was not significant enough in frequency or amplitude to control this disorder. After seeing a number of patients with this disorder in our center, we decided to implement a therapeutic exercise intervention program tailored to the patient's symptoms. The purpose of this study was twofold. The first purpose was to describe the entity of exercise induced motion intolerance. The second purpose was to describe the effects of vestibular physical therapy intervention on subjects with exercise induced motion intolerance. Vestibular physical therapy has been used successfully for patients with complaints of dizziness, imbalance, or other vestibular dysfunctions that are reproduced by movement activities [4-7]

Material and Methods

Fifteen patients presented with symptoms of exercise induced motion intolerance to the Department of Defense Spatial Orientation Center Between May of 1998 and November 2001. Diagnosis was based on history of a patient having symptoms of nausea, disequilibrium, and "dizziness" precipitated by bouts of exercise requiring head motion. There were eight males and seven females with an age range of 21-37 (with the exception of one patient age 60). The mean age was 23.5 years. Forty-seven percent (7/15) had a recent history of mild head trauma secondary to military training. Inquiry about smoking history was made because reports in the literature have suggested that smoking effects vestibular function and dizziness.[8]. Individuals underwent a full history, physical, and vestibular test battery. This included a standardized vestibular history and physical exam. Sinusoidal rotational chair testing was performed to assess vestibular ocular reflex gain, phase, and symmetry, and time constant evaluation step-testing (Micromedical Inc, Chatham, Illinois). Computerized dynamic posturography sensory organization test (CDP SOT) (Neurocom, Inc. Portland OR) was utilized to assess vestibular spinal reflex function. In addition, the Dynamic Gait Index (DGI) [9], the Activity Balance Confidence Scale (ABC),[10] and the Dizziness Handicap Index (DHI)[11] were administered. This battery of vestibular tests was used as an income/outcome measure to assess the results of the rehabilitation program. Time to return to full duty status and regular physical exercise was also documented. We believe that the return to duty tasks and rigorous physical training is the ultimate outcome measure.

Patients underwent a tailored therapeutic exercise intervention developed for each individual with this disorder. Traditional principles of therapeutic exercise were applied to the design of the vestibular rehabilitation regime. Stimuli procedures were selected to provoke vestibular perturbation. Patients performed voluntary and active motion tasks in pain-free available ranges of motion. Appropriate resistance was applied in which the patient performed at maximal tolerated effort. Diagonal and spiral patterns of motion were utilized to simulate functional tasks. External mechanical factors involved in the patient's operational environment such as gravity, acceleration, variable resistance, momentum, and maintaining body position on a fluctuating base of support were considered and included in designing each individuals exercise regimen.

In particular, the therapeutic intervention included a pre-conditioning phase and a therapeutic exercise phase. The pre-conditioning phase was comprised of a walk-jog-run program progressing over five steps from a timed walk followed by a timed jog to a three mile run. The therapeutic exercise phase included an overlay of head motion with the walk-jog-running, spiral and diagonals positional exercises, and exercises on an unstable surface.

Results

The mean time of return to duty for the study group was 4.6-week (range of 2.5-7.5 weeks). Post testing was performed when subjects achieved the functional outcome measure of running three miles asymptomatically. Vestibular assessment test means for DHI, ABC, DGI, and CDP SOT pre and post vestibular physical therapy are presented in Figure 1. Statistically significant differences were found for all assessment parameters after vestibular physical therapy intervention ($p < 0.05$). The DHI decreased by a mean of 17.3 points. The ABC scale improved by a mean of 18.5 points after vestibular physical therapy. The DGI increased a mean of 0.8 points. All subjects achieved the maximum possible points (24) on this assessment post therapy. The CDP SOT scores improved from a mean of 67.0 points pre physical therapy intervention to 71.3 post therapy. An example of the sinusoidal rotations chair test results is presented in Figure 2. All patients initially had a phase abnormality at 0.64 Hz on sinusoidal rotational chair testing. Post vestibular physical therapy all subjects returned to normal functional range at 0.64 Hz. This result was statistically significant ($p < 0.05$). The normalization of function was maintained in 11 of the 15 patients. We observed when obtaining patient history that five of our subjects were smokers. It has been suggested that smoking effects vestibular function. [8] Upon review, it was noted that the recurrence rate was significantly higher in smokers. Smokers demonstrated a 60% recurrence (3/5) as compared to non-smokers who demonstrated a 10% recurrence (1/10).

Discussion

Exercise induced motion intolerance appears to be a newly described clinical entity. This group of patients must be distinguished from other forms of dizziness so that the appropriate treatment may be administered. Many of these individuals have suffered mild head trauma prior to the onset of this disorder. The association of head trauma with balance disorders has been reported in the past, but specific links to exercise induced dizziness has not been discussed.[12] The consistent VOR phase abnormality at 0.64 Hz on sinusoidal rotational chair testing appears to represent an increase in velocity storage and results in a visual anticipation during head motion. In these patients the eyes lead the head only when the system is stressed during exercise involving head on neck rotation.[13] This observation is supported by the fact that patients do not experience dizziness when riding a stationary bike. These patients do not respond to traditional vestibular rehabilitation and appear not to demonstrate spontaneous resolution of symptoms. In addition, the appearance of this disorder in otherwise healthy individuals is associated with a significant emotional component. Individuals fear that they may not meet occupational performance standards, or could lose their jobs. Customized vestibular physical therapy intervention with an overlying head motion paradigm resulted in resolution of symptoms in all patients seen at our center. Objective outcomes scores and successful return to work, confirm the patients' reports that they feel better. Unfortunately, smokers face a significantly increased risk of recurrence. Individuals do respond to repeated vestibular physical therapy intervention but have consequentially been on limited duty for an extended period of time. This negative impact of smoking on successful control of vestibular disorders has been reported in the literature at a rate of 44 percent, which is lower than our 60 percent incidence in our exercise induced motion intolerance population.[11]

Conclusion

Exercise induced motion intolerance is a newly described clinical entity which can be diagnosed by history and a small number of objective vestibular physical exam findings. Individuals do respond to the appropriate type of customized vestibular rehabilitation, but do not respond to more traditional rehabilitation techniques. The military nature of our center allows us to see a number of patients with this disorder, and we plan to continue to refine our treatment strategy. We have already begun adding dynamic visual acuity tasking while individuals stand on an unstable surface, and are finding that this may hasten the recovery period. In addition, we are increasing our emphasis on diagonal and spiral patterns of motion that mimic functional activities of daily living and work. The advantage of these techniques is they can be administered in the field and can be tied to the specific operational tasking of the individual.

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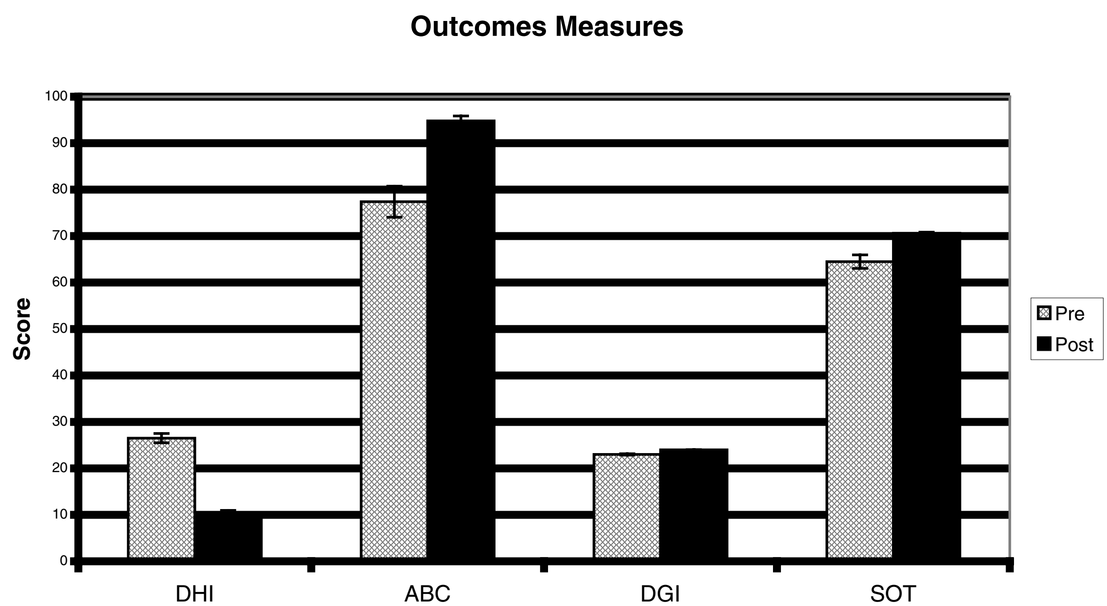
Figure 1

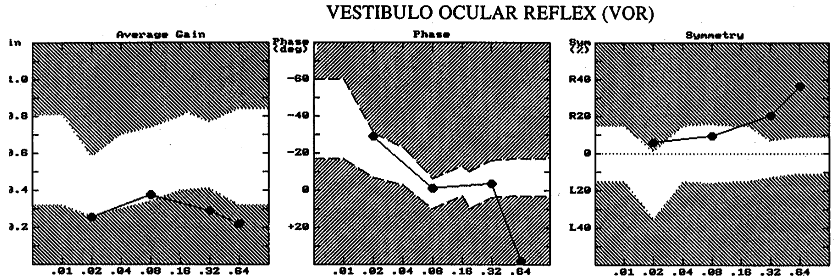


Improvement in DHI, ABC, DGI, and SOT after vestibular physical therapy. Hatched bars show pre-therapy measures and solid bars show post-therapy measures. Reduction in DHI indicates improvement whereas improvement in all other measures is denoted by a higher score. Improvement was seen in all four measures and was statistically significant for all four tests.

Figure 2

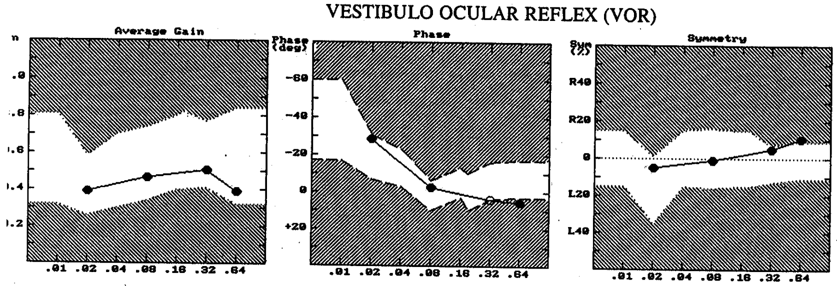
VOR Pre- and Post-Treatment

VESTIBULO OCULAR REFLEX (VOR)



Freq. Hz	Vel. d/s	Gain	Phase deg	Symmet. %
● 0.020	80	0.26	-29	R 5.9
● 0.080	80	0.38	-1	R 8.3
● 0.320	80	0.28	-3	R20.7
● 0.640	80	0.22	38	R36.4

VESTIBULO OCULAR REFLEX (VOR)



Freq. Hz	Vel. d/s	Gain	Phase deg	Symmet. %
● 0.020	80	0.39	-28	L 5.1
● 0.080	80	0.47	-2	L 1.1
● 0.320	80	0.51	4	R 5.0
● 0.640	80	0.39	5	R10.3

Sinusoidal Harmonic acceleration of VOR gain, phase, and symmetry in one patient from this group. The improvement in VOR phase after vestibular physical therapy was noted in all patients. In addition, this patient had abnormalities in gain and symmetry which improved with therapy, such gain and symmetry abnormalities were not noted in all patients.

La désorientation spatiale liée aux appareils vestibulaires chez les pilotes
(Spatial Disorientation Caused by Vestibular Organs in Pilots)

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RÉSUMÉ

Dans ce travail on a présenté les mécanismes de base de la désorientation spatiale causée par l'imperfection des appareils vestibulaires dans l'entourage spécifique des conditions de la désorientation spatiale chez des 20 pilotes observés à la Clinique Oto-laryngologique de IMA pendant 30 ans, qui ont révélés des incidents non conscients de la désorientation spatiale pendant le vol. 50 personnes du personnel aéronautique chez qui on n'observait pas de malaise suggérant la pathologie vestibulaire ainsi que des incorrections pendant le vol causées par la désorientation spatiale constituaient le groupe de comparaison.

Dans les deux groupes nous avons fait des tests ENG sur un appareil de la firme Tönnies-Jaeger. Aussi bien dans le groupe de contrôle nr I, comme dans le groupe nr II, après l'analyse du nystagmus spontané, l'examen du nystagmus positionnel et du nystagmus de position nous avons fait l'examen cinétique, selon le temps de l'examen, sous la forme du test selon Barany, le test accélération – décélération (A-D) ainsi que le test pendulaire sinusoïdal. Nous avons aussi fait le test calorifique quadruple avec la température de l'eau de 44 et de 27 degrés C. Nous estimions les résultats des tests dépendamment latence phase (Mpkwfocz.) et le nombre sommaire des coups (Siu.)

Dans les résultats des examens obtenus aussi bien dans le groupe de contrôle nr I comme chez les pilotes avec la désorientation spatiale - le groupe nr II, nous n'avons pas constaté de nystagmus spontané, positionnel et de position. Dans les examens avec des testes cinétiques dans le groupe de contrôle nous avons obtenu des résultats dans les limites de la norme - DP jusqu'à 20% et dans les examens calorifiques des rèsultats aussi corrects - CP et DP jusqu'à 20%.

Et dans les examens calorifiques chez les pilots du groupe nr II - avec la tendance à la désorientation spatiale agrandie nous avons obtenu deux sous - groupes:

1. Les pilotes avec le handicap de la fonction d'un vestibule
2. Les pilotes avec la prédominance directrice de l'origine périphérique.

Dans le premier sous - groupe, composé de 7 personnes, le handicap de la fonction d'un vestibule sur la base Mpwfocz. ou Siu. était dans les limites de 20-46%, dans deux cas il y avait aussi la prédominance directrice dans les tests rotatifs.

Dans le deuxième sous - groupe, composé de 13 pilotes, on a constaté chez 9 d'eux la prédominance directrice de l'origine périphérique de 21 à 40%, chez 3 d'eux les résultats dans les limites 14-18%, et seulement chez 1 d'eux la prédominance directrice était très basse et elle était d'environ 10%.

Du groupe de 20 pilotes qui signalaient la perte de l'orientation spatiale, chez 16 d'eux on a constaté les résultats CP et DP au-dessus de la norme admissible, ce qui constitue 20% du groupe.

Cette analyse nous montre que des changements asymptomatiques du potentiel statique et d'action, causés par différentes raisons et le plus souvent pas précisés, peuvent constituer, dans les conditions extrêmes, la raison de la catastrophe aérienne.

Cela justifie le point de vue que les pilotes chez qui on constate le handicap de la fonction de l'appareil vestibule de plus de 20% devraient être temporairement exclus des vols. Nos examens montrent aussi que les résultats incorrects ne corrèlent pas toujours avec le niveau des symptômes de la désorientation spatiale constatée. Les résultats incorrects des examens ont le caractère passager; dans les examens successifs, plus tard, on obtenait des résultats dans les limites de la norme.

On ne peut pas exclure que l'entourage extrême et traumatisant des conditions de travail du personnel aéronautique auxquelles l'organisme de l'homme n'est pas adapté pourraient être la raison de l'existence de la déviation de l'état normal dans les résultats des examens ENG.

Communication présentée lors du symposium RTO HFM sur la « Désorientation spatiale dans les véhicules militaires : causes, conséquences et remèdes », organisé à La Coruña, en Espagne, du 15 au 17 avril 2002, et éditée dans RTO-MP-086.

INTRODUCTION

L'organisme humain n'est pas adapté au vol de manière philogénétique, car pendant le vol, l'homme est influé par des accélérations, variables s'il s'agit de la direction et de la grandeur, aux valeurs non – rencontrées dans la vie quotidienne. L'imperfection des structures décidant de l'orientation dans l'entourage, c'est – à – dire des appareils vestibulaires, de l'organe de la vision, du système des propriorécepteurs, est l'expression de l'inadaptation. Au moment où le pilote reçoit des informations opposées de la part d'un de ces trois systèmes, il peut éprouver « une perte d'orientation de la position spatiale ». Sous ce terme nous pouvons comprendre la perte de la capabilité d'estimer sa position réelle par rapport à la Terre et la perception correcte de la gravitation, les difficultés de la détermination de la position géographique, de la direction et de la vitesse du vol et de l'angle du détour de l'avion.

De l'imperfection des appareils vestibulaires physiologiquement corrects décident quelques facteurs :

1) L'endolymphe qui se déplace pendant les mouvement de la tête influence de façon efficace, uniquement les récepteurs qui se trouvent sur la surface parallèle à la direction du mouvement.
2) Le seuil de l'excitabilité des plus sensibles canaux semicirculaires horizontaux est de - 0,05°/s², c'est pourquoi le mouvement de rotation de valeur inférieure de l'accélération angulaire n'est pas ressenti.
3) Il existe une dépendance disproportionnée entre la valeur de l'accélération angulaire et le temps exigé pour la reconnaissance du mouvement de rotation. Au moment de l'accélération 0,5°/s² la conscience du mouvement de rotation a lieu en 0,5 seconde, et à l'accélération de 0,25°/s² en 10 secondes.
4) Dans le cas des accélérations de grandes valeurs qui durent court, ont lieu, à cause d'une viscosité remarquable de l'endolymphe, des penchements de la coupole disproportionnement petits, ce qui peut être la cause de l'apparition d'informations faussement inférieures sur le mouvement existant.
5) Pendant une rotation prolongée il manque la possibilité de ressentir le mouvement de rotation stable à cause de la position de repos de la coupole.
6) Les organes otolithes ne sont pas capables de différencier la force de la gravitation de la force résultante pendant la présence simultanée des accélérations angulaires et linéaires.
7) On constate que le sentiment de l'écart du corps par rapport au pion, pendant le changement de la position de la tête de la position normale, devient de plus en plus pire.

Il existe tout un rang de causes et de mécanismes de l'existance de la désorientation spatiale en raison de l'inadaptation de l'oreille humaine aux conditions particulières du vol.

1) Vertiges de pression (Pressure vertigo).

Les vertiges de pression sont caractéristiques et ont lieu proportionnellement souvent chez le personnel aéronautique, en conséquence de la soudaine ouverture de la trompe auditive pendant la différence de la pression entre le milieu de l'entourage et la cavité de l'oreille moyenne. Ceci a lieu dans le cas de non - obstruction handicapé des trompes auditives, lors du vol avec le changement de la hauteur et surtout pendant l'abaissement. La soudaine ouverture de la trompe et le soudain changement de pression dans l'oreille moyenne déterminent le passage violent de l'endolymphe en provoquant le nystagmus non – fondé à cause du manque de l'accélération accompagnante. Cette situation peut créer une désorientation spatiale – l'impression du mouvement apparent.

2) Vertiges dans l'état d'appesanteur (Vertigo in weightlessness).

L'état d'appesanteur pendant les vols autour de la Terre produit des conditions particulières pour le système d'équilibre. Le manque de la force de la gravitation de façon particulière stimule les organes otolithes en provoquant une sensibilité redoublée de l'épithélium sensitif des canaux semicirculaires avec toutes les conséquences sous forme de la maladie cosmique, de perturbations de la coordination des yeux, de la tête et du corps, de la diminution de la tension des muscles. Ceci provoque l'apparition de l'illusion du caractère de la chute au devant, du ressentiment fautif des accélérations agissantes dans la direction opposée, l'illusion de la position la tête à l'envers.

3) Illusions somato – rotatives (Somatogyral illusion)

Les illusions sensorielles résultant de l'imperfection des canaux semicirculaires à la perception de la vitesse angulaire stable ce sont ***« le mouvement rotatif mortel » (graveyard spin)*** dans la vrille et la ***« spirale de la mort » (graveyard spiral).*** La menace dans le mouvement rotative dans la vrille et dans la spirale a lieu au moment où pendant un long exercice de ces mouvements on arrive à équilibrer le mouvement de l'endolymphe avec le mouvement rotatif, ce qui élimine le ressentimnt du mouvement rotatif. La sortie de ces manèvres cause le sentiment du mouvement rotatif dans la direction opposée malgré le fait que les instruments de bord informent sur le vol rectiligne. L'essai de la correction du vol uniquement à base des sentiments subjectifs amène à une nouvelle entrée dans un manèvre identique non – planifié, qui peut avoir une fin tragique. On peut prévenir la catastrophe en faisant une correction basant sur un point sûr d'orientation visuel ou à base des données des instruments de bord.

4) Désorientation résultant de l'action des accélérations Coriolis (Coriolis illusion).

L'effet important résultant de l'activation des organes vestibulaires pendant le vol c'est le phénomène de Coriolis, quand apparaît un mouvement qui se compose du mouvement rotatif et du mouvement linéaire coexistant dans le même temps.

L'effet Coriolis (Ecor) est directement proportionnel à la vitesse linéaire stable du système qui est soumis au mouvement (W1), de la vitesse angulaire supplémentaire du mouvement rotatif (W2) et du temps de leur fonctionnement (t).

$$Ecor = W1 \times W2 \times t$$

Le résultat de ceci c'est le ressentiment du mouvement sur une nouvelle surface où n'existe pas le mouvement réel. Dans le cas de grandes vitesses d'avions modernes même un tout petit mouvement de la tête, causé par les mouvements de respiration, peut contribuer à la perturbation de l'orientation spatiale en résultat de l'effet Coriolis.

5) Illusion somato – gravitationnelle (Somatogravic illusion).

Les ressentiments fautifs de la position du corps par rapport à la force de la gravitation et à l'orientation concernant le plafond du vol sont soumis aux informations contraires des domaines des canaux semicirculaires, des otolithes et des propriorécepteurs au ressentiment précis des accélérations linéaires positives et négatives et des accélération angulaires.

Cela résulte du fait que ce qui est ressenti le plus c'est la résultante des forces en action et non des vecteurs (force de la gravitation, force centrifuge, force d'inertie).

a) Perturbation de l'orientation au moment du changement de la vitesse.

Une mauvaise évaluation de la position de l'avion peut avoir lieu pendant un vol rectiligne au moment d'un soudain changement de vitesse. La force résultante qui est produite, composée de force d'inertie et de force de la gravitation, est identifiée comme force d'attraction terrestre – cela est cause de l'illusion de montée /le nez vers le haut/ pendant l'accélération et de chute (le nez vers le bas) pendant le freinage.

b) Perturbation de l'orientation pendant le détour de coordination.

Le ressentiment fautif du mouvement rectiligne peut avoir aussi lieu pendant le manèvre de détour de coordination de l'avion, quand la résultante de la force de la gravitation et de la force centrifuge se couvrent avec l'axe du pion par rapport au pilote. En effet de ceci il ne ressent pas le manèvre du détour, car il ne reçoit pas les informations sur les accélérations angulaires et il identifie la résultante des forces en action avec la force de la gravitation.

6) Illusion oculo – gravitationnelle (Oculogravic illusion).

Pendant l'accélération linéaire sous l'influence de la force de l'attraction terrestre, ce qui n'est pas différencié par le labyrinthe, il y a un conflit entre les ressentiments somato – gravitationnels et les impressions visuelles informant sur le caractère du mouvement existant. On peut avoir l'illusion du déplacement des objets qui se trouvent dans le champ de vue de différentes directions. Cette illusion est image de la fonction des otolithes et n'est pas accompagnée ni par le nystagmus ni par des vertiges.

Les conséquences de différentes formes de désorientation spatiale dans l'aviation peuvent dépendre de la conscience de l'illusion éprouvée.

On différencie deux types de désorientation:

Type I – Désorientation dans le cas où le pilote de différentes raisons n'est pas conscient de l'incorrecte position de l'avion par rapport à ses propres sentiments.

Type II – Désorientation dans le cas où le pilote est conscient des sentiments incorrects et les confronte avec les données des appareils de bord.

Le type I paraît rarement et le plus souvent se termine par une catastrophe aérienne, car le pilote base sur les ressentiments subjectifs, n'essaye pas de retrouver la bonne position de l'avion. Cepndant le type II de désorientation apparaît assez souvent, surtout pendant les vols sur les avions modernes. De convenables procédures, accentuées pendant le processus de formation des pilotes, permettent dans ce cas – là d'éviter une procédure incorrecte et de prévenir une catastrophe aérienne.

L'OBJET DU TRAVAIL

L'objet du travail, c'est de présenter les cas de désorientation spatiale chez les pilotes observés dans la Clinique Otolaryngologique de l'Institut de la Médecine Aérospatiale dans les dernières trente années, chez lesquels nous avons constaté de petites irrégularités passagères grâce aux examens ENG.

MATERIEL

Les examens electronystagmographiques des appareils vestibulaires ont été organisés dans 2 groupes de personnel aéronautique:

Groupe I (de contrôle) - 50 personnes du personnel aéronautique dans l'âge de 25 à 50 ans. Chez les pilotes de ce groupe il n' y avait ni perturbations suggérant une pathologie vestibulaire ni perturbations lors des vols qui pouvaient être conséquence d'une désorientation spatiale.

Groupe II – 20 membres du personnel aéronautique dans l'âge de 21 à 47 ans, qui ne déclaraient pas de perturbations du domaine des appareils vestibulaires dans la vie quotidienne, mais pendant le vol il y avait chez eux des troubles de perte du positionnement spatial et, à cause des problèmes qu'ils déclaraient ou à cause des fautes comises, ils ont été soumis à un contrôle à l'Institut de la Médecine Aérospatiale.

METHODES D'EXAMEN

Les examens ont été menés sur un appareil informatisé ENG de la société Tönnies – Jaeger. Aussi bien dans le groupe I comme dans le groupe II, après l'analyse du nystagmus spontané avec les yeux ouverts et fermés, après l'examen du nystagmus positionnel dans 6 positions et du nystagmus de position, nous avons effectué un examen cinétique dépendant de la période des examens sous forme de : test selon Barany au freinage de 90°/s, le test accélération – décélération (A – D) avec l'accélération négative et positive 5°/s² avec la vitesse de rotation stable 60°/s et le test pendulaire au changement sinusoidale du stimulant, au plein temps du cycle de la rotation 30 secondes avec une maximale vitesse angulaire 90°/s. Nous avons effectué aussi dans les deux groupes un test calorifique quadruple avec la température de l'eau de 44° et de 27°C.

Dans le cas de doutes diagnostiques nous avons organisé des tests centraux : des test symphysaires et de conduite et des tests opto-cinétiques.

Suivant le genre de test nous avons estimés les résultat à base de la vitesse angulaire maximale de la phase lente du nystagmus (Mpkwfocz.), de l'amplitude, de la fréquence, du nombre sommaire des coups (Siu.) et du type de la réaction opto-mouvementée.

RESULTAT DES TESTS

Dans les résultats des tests, aussi bien dans le groupe I que parmi les pilotes avec les perturbations d'orientation spatiale – groupe II, nous n'avons pas constaté de nystagmus spontané, positionnel et de position.

Pendant les examens à base des essais cinétiques, dans le groupe de contrôle, nous avons obtenu un résultat dans les limites de la norme – DP jusqu'à 20%, et dans les tests calorifiques aussi des résultats corrects – CP et DP jusqu'à 20%.

Cependant pendant les tests calorifiques chez les pilotes du groupe II – avec la tendance à une désorientation spatiale excessive nous avons reçu deux sous – groupes :

1) Les pilotes avec le handicap de la fonction d'un vestibule.

2) Les pilotes avec la prédominance directrice de l'origine périphérique.

Dans le premier sous – groupe (tableau 1), composé de 7 personnes, le handicap de la fonction d'un vestibule déterminé à base des valeurs les plus corrélatives – Siu. et Mpwfocz. était dans les limites 20-46%, dont dans 2 cas coexistait aussi la prédominance directrice dans les tests rotatifs. Dans le tableau nous avons aussi décrit les perturbations qui ont eu lieu pendant le vol.

Dans le second sous – groupe (tableau 2 et 2a), comptant 13 pilotes, chez 9 nous avons constaté la prédominance directrice d'origine périphérique de 21 à 40%, aussi à base de Siu. et Mpkwfocz.; chez 3 pilotes les résultats étaient dans les limites 14 – 18% et seulement chez 1 personne la prédominance directrice était très basse et elle a atteint environ 10%. Dans ces tableaux nous avons présenté les troubles qui ont eu lieu chez les examinés pendant les vols.

La corrélation des résultats incorrects dans les tests rotatifs et dans les tests calorifiques a eu lieu dans 4 cas, chez 3 personnes examinées la prédominance directrice dans les essais cinétiques était plus grande que dans les tests rotatifs et a constitué la base pour l'estimation des examinés.

ANALYSE DES RESULTATS

Dans le groupe de 20 pilotes qui ont informé de la perte de l'orientatation de la position spatiale, chez 16 d'eux on a constaté des résultats CP et DP dépasant la norme admissible, ce qui constitue 80% du groupe et est la preuve de l'existence dans leur cas de la désorientation spatiale d'origine vestibulaire. Il faut en conclure que dans le groupe des 4 autres personnes (20%), chez lesquelles on n'a pas constaté d'écart de norme dans les examens ENG, les causes de désorientation spatiale étaient probablement de nature psychologique.

De cette analyse résulte que les changements asymptomatiques du potentiel statique et d'action des appareils vestibulaires, causés par différentes raisons et le plus souvent pas précisés peuvent constituer, dans des conditions extrêmes, des symptômes de perte de position aérienne et peuvent être raison d'une catastrophe aérienne. Cela justifie le point de vue que les pilotes chez lesquels on trouve le handicap de la fonction de l'appareil vestibulaire de plus de 20% devraient être temporairement exclus des vols.

Ces examens montrent aussi que les résultats incorrects ne corrèlent pas toujours avec le niveau des symptômes de la désorientation spatiale constatée. Les résultats incorrects des examens ont un caractère passager. Dans les examens successifs, plus tard, on a reçu des résultats ENG dans les limites de la norme.

On ne peut pas exclure que l'entourage extrême et traumatisant des conditions de travail du personne l aéronautique auxquelles l'organisme de l'homme n'est pas adapté pourraient être la raison de l'existence de la déviation de l'état normal dans les résultats des examens ENG.

CONCLUSIONS

1) Parmi le personnel aéronautique sporadiquement on retrouve des cas asymptomatiques d'asymétrie vestibulaire ou de prédominance directrice qui se manifestent sous forme de désorientation spatiale dans des conditions extrêmes de vol.
2) Dans le groupe des pilotes observés à cause de désorientation spatiale chez 80% nous avons constaté des résultats dépassant la valeur 20%DP dans les essais cinétiques ou CP ou DP dans les examens calorifiques, pendant que dans le groupe de contrôle les résultats obtenus étaient dans les limites de la norme.
3) Les pilotes chez lesquels on a constaté le handicap de la fonction de l'appareil vestibulaire dépassant 20% devraient être temporairement exclus des vols.
4) Il faut qualifier pour les vols dans des conditions difficiles (nuit, mauvaises conditions atmosphériques), avec beaucoup de précaution, les pilotes avec le handicap de la fonction de l'appareil vestibulaire même dans les limites 15 – 20%.
5) Les valeurs des résultats incorrects des examens ne corrèlent pas toujours avec les symptômes de désorientation spatiale constatée.
6) Les résultats incorrects des examens peuvent avoir caractère passager, dans des examens successifs, plus tard, on a reçu des résultats dans les limites de la norme.

Tableau 1. Pilotes avec le handicap de la fonction d'un vestibule.

	Anomalies ayant lieu pendant le vol	**Handicap de la fonction du vestibule**
1	Pilote, 31 ans, effectue des vols sur Mig – 21 Sentiment d'incertitude dans l'air ; crainte envers les vols pendant la nuit.	- droit Siu - Mpkwfocz. A – **32.6%** **46.0%**
2	Pilote, 43 ans, effectue des vols sur Mig – 21 Sentiment d'incertitude dans l'air, surtout lors des vols pendant la nuit.	- gauche Siu - Mpkwfocz. A – **28.7%** **34.9%** B – **25.6%** **21.1%** D – **21.2%** ---
3	Navigateur, 43 ans, effectue des vols sur Mi – 2 Pendant les vols, dans les moments de mouvements violents de tête il avait le ressentiment du passage de l'horizon vers le côté droit.	- gauche Siu - Mpkwfocz. A – **35.7%** **34.6%** B – **25.3%** **21.6%**
4	Aspirant, 21 ans, en formation aérienne. Crainte envers les vols; sentiment d'incertitude dans l'air.	- gauche Siu - Mpkwfocz. A – **28.1%** **39.5%**
5	Pilote, 39 ans, effectue des vols sur TS – 8 Iskra. Pendant le vol il a le sentiment du penchement de l'avion sur l'aile gauche. En plus le pilote a l'impression de la rotation de l'avion autour du pion vers le côté gauche.	- droit Siu - Mpkwfocz. A – 16.8% **20.9%**
6	Pilote, 31 ans, effectue des vols sur Mig – 21 Informe de l'incertitude dans l'air. Pendant les vols de nuit l'atterissage n'est pas sûr.	- gauche Siu - Mpkwfocz. A – 19.9% **20.9%** D – 18.1% ---
7	Pilote, 47 ans, effectue des vols sur An – 2 Pendant les vols, lors des manèvres de détour, il avait l'impression d'un passage violent de l'horizon vers la direction opposée par rapport au détour en cours.	- droit Siu - Mpkwfocz. A – **23.6%** **23.1%**

A – résultats des essais calorifiques
B – résultats des examens rotatifs
C – résultats du test accélération – décélération
D – résultats du test pendulaire soutenu
Siu – nombre sommaire des coups
Mpkwfocz - la vitesse angulaire maximale de la phase lente du nystagmus
23,1% (BOLD) - résultats incorrects

Tableau 2. Pilotes avec prédominance directrice d'origine périphérique.

	Anomalies ayant lieu pendant les vols	Prédominance directrice du nystagmus
1	Pilote, 37 ans, effectue des vols sur Lim – 6. Pendant les vols sans visibilité de la terre (pendant la nuit, dans les nuages) il ressent des penchements de l'avion vers le côté gauche.	- de côté gauche Siu - Mpkwfocz. A – **25.7%** **25.3%** C – 18.2%
2	Pilote, 41 ans, effectue des vols sur An – 2 Sentiment d'incertitude pendant les vols dans les nuages ou les vols de nuit.	- de côté droite Siu - Mpkwfocz. A – **20.6%** **23.6%**
3	Pilote, 36 ans, effectue des vols sur Lim – 6. Pendant le vol sentiment du penchement de l'avion sur l'aile gauche	- de côté gauche Siu - Mpkwfocz. A – **20.8%** **20.5%** B – 13.6% 17.8%
4	Pilote, 25 ans, effectue des vols sur Lim – 6. Informe du sentiment de l'incertitude dans l'air.	- de côté gauche Siu - Mpkwfocz. A – **26.5%** **30.1%** B – 17.1% 16.6% C – **24.2%**
5	Pilote, 37 ans, effectue des vols sur Mig – 21 Dans des conditions atmosphériques difficiles (dans les nuages) inconsciemment il volait à rebours (sens dessus – dessous)	- de côté droite Siu - Mpkwfocz. A – 18.2% 17.6% B – **30.5%** **20.6%** C – **29.8%** **---** **D – 25.4%** **---**
6	Pilote, 42 ans, effectue des vols sur des avions de transport. Informe du sentiment de l'incertitude dans l'air et a peur des vols de nuit.	- de côté droite Siu - Mpkwfocz. A – **39.1%** **39.7%** B – **28.8%** 10.9% C – **39.3%** **---** **D – 20.1%** **---**

Tableau 2a. Pilote avec prédominance directrice d'origine périphérique.

	Anomalies ayant lieu pendant le vol	Prédominance directrice du nystagmus
1	Pilote, 30 ans, effectue des vols sur An - 2 Profil d'atterissage incorrect avec penchement sur l'aile gauche.	- de côté gauche Siu - Mpkwfocz. A – **22.6%** 18.1% B – **25.8%** 18.3% C – **39.5%**
2	Pilote, 38 ans, effectue des vols sur Su - 20 Pendant les vols de nuit profil d'atterissage incorrect avec penchement sur l'aile gauche.	- De côté gauche Siu - Mpkwfocz. A – **23.7%** **21.6%** C – 17.1% ---
3	Pilote, 27 ans, effectue des vols sur Lim - 5 Informe sur le sentiment d'incertitude dans l'air.	- De côté droite Siu - Mpkwfocz. A – **32.4%** **33.2%** B – **31.1%** 17.1% D – **26.5%**
4	Pilote, 38 ans, effectue des vols sur des avions sanitaires. Pendant les vols il a l'impression du passage de l'horizon vers le côté gauche.	- De côté droite Siu - Mpkwfocz. A – 13.9% 14.2%
5	Pilote, 41 ans, effectue des vols sur Lim - 6. Pendant le vol, quand il tourne de façon maximale la tête il a le sentiment du renversement de l'avion sur le dos ; le sentiment du tonneau.	- De côté gauche Siu - Mpkwfocz. A – 16.4% 18.0% C – 12.0%
6	Pilote, 43 ans, effectue des vols sur Jak - 40 Pendant les vols de nuit profil d'atterissage incorrect avec penchement sur l'aile droite.	- De côté droite Siu - Mpkwfocz. A – 10.3% 11.5% C – 9.0% ---
7	Pilote, 38 ans, effectue les vols sur Lim - 6 Pendant les vols de nuit (en prenant de la hauteur) pendant le détour il a l'impression de faire des tonneaux vers la direction opposée.	- De côté droite Siu - Mpkwfocz. A – 10.6% 17.1%

Vestibular Stimuli May Degrade Situation Awareness Even When Spatial Disorientation is not Experienced

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Summary

Spatial disorientation (SD) is an important contributor to aviation mishaps. Misleading acceleration stimuli during flight are one of the main causes of SD. SD is associated with a loss of situation awareness (LSA) and the commission of dangerous errors, yet little is known concerning the specific interactions among SD, LSA, and human error. While SD is likely to be an important contributor to LSA and human error, the interaction is complicated because acceleration stimuli to the vestibular organs degrade a person's well-being and performance even when spatial disorientation (SD) is not experienced. This paper points out theoretical gaps in knowledge concerning LSA, SD of vestibular origin, and vestibular effects other than SD. The authors argue for a wider consideration of the ways in which vestibular acceleration stimuli contribute to unsafe conditions for vehicle operators. While vestibular acceleration stimuli can elicit SD, they can also challenge psychomotor performance, visual performance, and certain aspects of cognition. A complete approach to the study of acceleration-induced human error and LSA should assess these various decrements in human functioning simultaneously, so the relative contribution of each decrement to the commission of error can be understood and the interactions among the decrements described.

Introduction to Spatial Disorientation (SD)

Modern vehicles and displays expose personnel to disorienting real or apparent accelerations. Real acceleration refers to physical acceleration of the human body, such as during flight maneuvers. Real acceleration can include sudden accelerations that are hazardous to one's skeleton and internal organs or sustained high-G maneuvers requiring special precautions to prevent G-induced loss of consciousness (GLoC). In this paper, the phrase "real acceleration" will denote acceleration stimuli that affect the vestibular and somesthetic receptors without directly producing body damage via mechanical shock or GloC via cardiovascular mechanisms. (Note, however, that vestibular effects complicate the view that GloC is purely a cardiovascular phenomenon, according to Cheung & Bateman, 2001).

The second category of acceleration stimuli mentioned in the last paragraph was "apparent acceleration." Apparent acceleration refers to visual, auditory, or somesthetic display conditions conducive of illusions of self motion or orientation, such as occur during exploration of a virtual environment or "flying" in a simulator. Although real acceleration is the focus of this paper, the vestibular system also responds to whole-field visual motion, which stimulates some of the same brain centers that process whole-body motion stimuli (Dichgans & Brandt, 1978). Moreover, since visually-

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induced illusions of self motion (known as vection) can be produced during certain conditions of flight (Gillingham & Previc, 1996), apparent acceleration is not merely a simulator issue. While an episode of SD during exposure to a simulator or virtual environment would not be dangerous, the vestibular aftereffects of exposure to apparent acceleration are potentially hazardous (Stanney, ed., 2002), as are the effects of vection illusions during real flight (Gillingham & Previc, 1996).

There has been some controversy over how narrowly SD should be defined (Navathe & Singh, 1994; Previc, Yauch, DeVilbiss, Ercoline, & Sipes 1995; Cheung, 1995; Cheung, Money, & Sarkar, 1996), but in the aviation setting, a commonly used definition of SD is a failure by the aviator (or flight crew) "…to sense correctly the position, motion, or attitude of the aircraft or of him/herself within the fixed coordinate system provided by the surface of the earth and the gravitational vertical" (page 419, Benson, 1988). SD can be caused by illusions of body position, motion, or orientation whose origins lie in the visual, somesthetic, and vestibular modalities. Episodes of SD are often distinguished from geographic disorientation or "getting lost", due to a navigational error that affects an aviator's appreciation of his route, bearing, latitude, or longitude within fixed coordinates on the surface of the earth (Benson, 1988; United States Naval Flight Surgeon's Manual, 1991; Gillingham & Previc, 1996; Ercoline & Previc, 2001). Note that misjudgments of altitude are usually considered part of SD (Lyons, Ercoline, Freeman, & Gillignham, 1993; Previc, Yauch, DeVilbiss, Ercoline, & Sipes, 1995), because the operational characterization of SD includes a misperception or lack of awareness concerning the magnitude or direction of aircraft control and performance parameters, including altitude, attitude, and vertical velocity (Gillingham, 1992)

Estimates vary widely concerning the prevalence of SD-related mishaps (Lyons, Ercoline, Freeman, & Gillingham, 1994). For example, in U.S. rotary-wing operations, when estimates of SD-related mishaps are calculated as a percentage of total mishaps by service, estimates vary from 30% for the U.S. Army (Braithwaite, Durnford, Crowley, Rosado, & Albano, 1998) to 42% for U.S. Marine Corps (Mason, 1997). Gillingham (1992), Lyons et al. (1994) and Johnson (2000) believed that most published SD estimates were too conservative. Gillingham (1992) pointed out problems with mishap classification and conjectured that SD caused as many as 2-3 times more U.S. Air Force mishaps than the incidence statistics would lead us to believe. Johnson, (2000) stated that SD mishaps in the U.S. Navy may be twice as likely as the statistics would indicate, accounting for 26% of all the most serious (Class A) Mishaps (U. S. Naval Flight Surgeon's Manual, 1991) and claiming nearly three times more lives than non-SD mishaps. SD mishaps are often fatal, accounting for the loss of about 40 lives per year in the U.S. Air Force, Navy and Army combined (Braithwaite et al., 1998; McGrath, 2000).

Lyons et al. (1994) discussed several classification problems they observed in the mishap data, including failure to clarify the relationship of SD to mishaps that involved continuing VFR flight into adverse weather. Lyons et al. (1994) noted that a simple change in the accident reporting form increased the rate of categorization of accidents as SD-related. Whereas the old accident investigation form listed "visual illusions" and "disorientation/vertigo" as choices, the new form substituted the currently-accepted categories of SD as possible choices on the form. The three categories of SD listed on the form were type 1 (unrecognized), type 2 (recognized), and type 3 (incapacitating). The result of this change was an increase in choosing SD as a causal factor during low-level navigation, from 7% with the old form (FY86-FY89) to 67% with the new form (FY90-91). One of the key advantages of the newer form was that it listed "unrecognized SD." This change implicitly promoted the selection of SD as a mishap contributor in cases where the pilot did not report having suffered an acute and recognizable vestibular illusion, such as an attack of "the leans", but the accelerations the pilot experienced and the control inputs the pilot made indicated that the pilot was spatially disoriented (Benson, 1988).

The vestibular organs have been the focus of many past efforts to understand the SD aviators experience during flight. The vestibular organs are important because they constitute the key sensory modality specifically evolved to detect acceleration of the head in inertial space, yet they are not designed to provide veridical body orientation information within the unusual sensorimotor and force environments that occur during aerospace operations. Military aviators are familiar with the classic “vestibular” (or more accurately, vestibular/somesthetic/visual) spatial orientation illusions that are associated with SD during the physical accelerations occurring in flight. There are numerous, well-documented illusions that have a vestibular component, including the leans, the somatogravic/oculogravic illusions, the elevator illusion, the somatogyral/oculogyral illusions, the Coriolis cross-coupling illusion, the G-excess effect, the giant hand illusion, the inversion illusion, the visual vection illusion, and the Gillingham Illusion (Benson, 1988; U.S. Naval Flight Surgeon’s Manual, Third edition, 1991; Gillingham & Previc, 1996; Cohen, 1973; Ercoline, Devilbiss, Yauch, & Brown, 2000). Similar illusions of perceived motion or posture are associated with the aftereffects of space flight (Nicogossian, Huntoon, & Pool, eds., 1989), simulator exposure (McCauley, ed, 1984), and virtual environment exposure (Stanney, ed., 2002).

One of the more common “vestibular” SD illusions in flight is “the leans” (Benson, 1988), which entails an erroneous feeling of roll orientation. A typical case occurs during recovery from a turn while flying without outside visual cues. Upon recovery from the turn, the aviator may feel banked when he or she is actually flying “wings level.” (The vestibular mechanisms for this illusion are explained by Benson, 1988 and by Gillingham & Previc, 1996.) The fact that the leans and numerous other SD illusions have been named and explained does not imply the victim explicitly recognizes them during an episode of SD. In fact, SD usually occurs without being recognized (Braithwaite et al., 1998). One example of unrecognized SD (known as type 1 SD) occurs during mild acceleration of a helicopter. Hovering a helicopter is a demanding visual exercise requiring the aviator to use at least three visual reference points continually (one forward, one right and one left) to maintain the hover over a particular spot. In conditions of low visibility, it is difficult to find visual reference points and the aviator may begin to drift slowly in a linear fashion (right, left, forward or back). In such a situation, the acceleration stimulus might be below the threshold of vestibular and somesthetic detection and with visual cues degraded, the aviator will not appreciate the drift that is occurring. If the aviator does not attend to the flight instruments immediately, LSA will occur, the drift will go undetected and the helicopter might impact a nearby object. This sub-threshold acceleration event is clearly a case of SD in that it entails feeling one is not moving when one is. This example was chosen to illustrate three important points: 1) SD can occur without being recognized; 2) SD can occur without the presence of a strong acceleration stimulus; 3) An illusion with a vestibular component does not have to be categorizable as one of the classical “vestibular” SD illusions in order to qualify as an SD event. For further information on disorienting illusions with a vestibular component, the reader should refer to Lawson, Sides, and Hickinbotham (2002, ed. Stanney) and chapter 3.210, volume 1 of Boff and Lincoln, 1988.

Spatial Disorientation (SD) Versus Loss of Situation Awareness (LSA)

Situation Awareness is a more general concept than SD. In 1994, Dominguez counted 15 different definitions for SA, and the number has grown since then. However, Endsley’s definition (1988, p. 97) is the one most commonly cited: “the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.” Thus, SA encompasses at least three concepts: perception (of cues), comprehension (of significance of cues), and projection (of future events). The concepts that characterize SA appear to be convergent with attention (Taylor, 1990), workload (Hendy, 1996; Vidulvich, Stratton, Crabtree, & Wilson, 1994), pattern recognition (Kass, Herschler, & Companion, 1991), mode error (Sarter & Woods, 1995), mental models (Mogford, 1997), platform-specific flight experience (Carretta & Ree, 1996), and certain aspects of memory (Sarter & Woods, 1991; Fracker, 1988). Selective attention is one of the constructs that should be especially convergent with SA, because selective attention is the preferential selection process that determines which environmental cues are perceived and comprehended (Endsley, 2000). The critical importance of attention to SA was supported by Taylor (1990), who empirically derived three cognitive dimensions of SA: 1) demand on attentional resources (related to instability, variability, and complexity of the situation), 2) supply of attentional resources (related to the human operator's state of arousal, spare mental capacity, concentration, and division of attention), and 3) understanding of the situation (related to quantity and quality of information received and understood and familiarity with the situation).

Initial attention to and perception of environmental cues appear to be important to understanding the relation between LSA and accidents. Endsley (1995) analyzed 24 major air carrier accidents reported by the National Transportation and Safety Board from 1989-1992. Endsley identified human error (excluding error during maintenance operations) as a contributing factor in 17 of the 24 accidents. She created several categories of contributory factors for human error: decision-making, SA, physiological, procedural, and psychomotor. The most common contributing factor was loss of SA, accounting for 15 (88%) of the 17 human error accidents. For the 15 accidents in which SA error occurred, a total of 32 SA errors were present, 23 of which (72%) involved level 1 SA errors, i.e., a failure to perceive the needed cues. However, many LSA accidents involved additional factors that contributed to the SA error. Four of the accidents involved some sort of physiological degradation, usually fatigue. Six accidents involved a violation of procedure, usually involving omitting a task. Four of the accidents involved bad decision-making, such as proceeding into inclement weather and neglecting to fly by instruments when needed, or continuing on what should have been called an aborted or missed approach. Two accidents involved psychomotor skills needed to control the aircraft.

Jones and Endsley (1996) analyzed 143 incidents reported in the database of the Aviation Safety Reporting System (1989-1992). They found that of 143 incidents reported, 111 (78%) involved SA errors on the part of the flight crew and 32 (22%) involved SA errors on the part of air traffic controllers. Endsley employed the aforementioned taxonomy containing three levels of SA: 1) perception of needed cues in the current situation, 2) comprehension of the current situation and the relevance of the cues to one's goals, 3) projection from current events to future status. The incidents summarized by Jones and Endsley (1996) included 262 different SA errors, 76% of which could be traced to type 1 LSA – a simple failure to perceive the needed information (or to perceive it correctly). Failure to perceive the needed information could be broken down further into 5 subcategories, as follows: a) data not available, b) hard to discriminate or detect data, d) failure to monitor or observe data, d) misperception (not due to sensory illusions, but to factors such as negative interference and confusing currently available information with the information sought), e) Memory Loss (forgetting of information previously in awareness). The most common reason for a type 1 SA failure (to perceive the needed cues) was found in subcategory c) – failure to monitor or observe available data, which comprised 35% of total SA errors. A failure to monitor or observe relevant data that is readily available can be attributed to a number of factors, among which momentary task distraction and high workload are the most important (23% of total SA errors).

Several inferences can be drawn from the accident and incident findings of Endsley (1995) and Jones and Endsley (1996). Firstly, the findings indicate that LSA does not often occur in isolation from other contributors, such as fatigue, errors of omission, or failing to switch to instrument flight when needed. Secondly, the findings imply that when LSA occurs, aviators are not usually losing SA due to a high-level failure of cognitive interpretation, comprehension, or prediction of events, but rather because of a simple failure to perceive or attend to needed data. Concerning the type of data that is missed, studies of aircraft mishaps indicate that failure to attend to data from the altitude indicator is crucial (Flight Safety Foundation, 1999). It is also likely that since aviators spend much of their scan time on the attitude indicator and the directional gyro (Simmons, Lees, & Kimbal, 1978), so information from these instruments may be especially affected by periods when one is attending to other displays or tasks.

A similar tendency not to recognize hazards during moments of distraction has been noted by SD researchers. The typical SD mishap occurs when visual attention is distracted from the aircraft's orientation instruments and the horizon is not visible or not being monitored (McGrath, 2000). The majority of SD mishaps are related to type 1 or unrecognized SD. Specifically, 100% of U.S. Air Force SD mishaps during 1990-91 were related to unrecognized SD (Lyons et al., 1993), while 90% of U.S. Army SD mishaps from 1987-1995 were related to unrecognized SD (Braithwaite, Groh, & Alvarez, 1997, Durnford, Crowley, & Rosado, 1995). In contrast, relatively few SD mishaps are attributed to SD that is recognized (type 2) or SD that is completely incapacitating (type 3).

Mishap findings from civil aviation correspond to the trends mentioned above. In civil aviation, one of the most frequent mishap categories is controlled flight into terrain (CFIT), wherein the crew flies a serviceable aircraft into the ground without being aware they are doing so, or with awareness coming too late. By the end of the 1980s, better training and technology had reduced the likelihood of midair collisions and wind-shear accidents dramatically, but the CFIT accident fatality category had grown to 81% of the total (Flight Safety Foundation, 1996). Among worldwide airlines from 1991 to 1995, there were more CFIT accidents than any other type (Flight Safety Foundation, 1996). According to a task force sponsored by the Flight Safety Foundation (1996), the International Civil Aviation Organization, and the U.S. Department of Transportation, there are two basic causes of CFIT accidents: "…the flight crew's lack of vertical position awareness or their lack of horizontal position awareness in relation to the ground, water, or obstacles. More than two-thirds of all CFIT accidents are the result of altitude error or lack of vertical situational awareness" (page 3.8, CFIT Education and Training Aid, Flight Safety Foundation, 1996).

Thus, the incident and mishap data from various settings suggest that SD mishaps, LSA incidents, and CFIT accidents frequently occur under similar conditions; namely, when there is a failure to perceive the position (or motion) of the aircraft correctly. Such outcomes usually occur under conditions of distraction with other flight tasks or high workload. However, while distraction and workload are very important accident contributors, they do not usually cause accidents in isolation from other factors. Rather, distraction becomes hazardous because one's attention is drawn away from cues concerning aircraft position while one's aircraft is flying close to the earth or other significant objects. In fact, the majority (60.9%, according to Figure 10 of the CFIT Education and Training Aid, Flight Safety Foundation, 1996) of all civil aviation accidents occur during the descent, approach, and landing phases of flight, when distraction and workload are higher and the margin for positional error is lower than during the cruise portion of flight (4.5%). Typically (Flight Safety Foundation, 1998, 1999), approach-and-landing accidents are classified as decision errors because the flight crew decided to descend below the minimum height for a "go around" decision, despite the absence of adequate outside visual cues. However, CFIT is explicitly recognized when it is obvious the flight crew lost accurate awareness of their position relative to the ground.

The authors believe that the inability of an aviator (or a flight crew) to accurately perceive aircraft position intuitively and without reliance upon visual cues (from flight instruments or the outside world) is a major crux of the aviation mishap problem. Gillingham (1992) pointed out that the majority of LSA mishaps in his database would not have happened if the pilots had not been spatially disoriented. Maintaining spatial orientation is a key prerequisite to maintaining situation awareness, but it cannot be done in present-day flight operations unless one is attending to the appropriate visual cues. Unfortunately, many of an aviator's distracting secondary flight tasks are also of a visual nature so continuous attention to one's spatial orientation cannot be maintained using current visual displays. The problem concerning the allocation of limited attentional resources is compounded by the fact that attentional resources will be drawn to more natural and salient body cues concerning orientation, which in the environment of flight are not veridical. In other words, the problem of LSA in flight is not caused merely be the formation of an incomplete mental model due to attentional limitations; rather, the problem is the formation of an incorrect, yet persuasive mental model due to one's subconscious tendency to rely upon vestibular and somesthetic orientation cues.

For these reasons, current flight displays offer ample opportunity for falling prey to distraction from primary flight cues. New instruments are under development that should help to decrease this problem by presenting visual information in fewer and more intuitive displays (Still & Temme, 2001). Also, investigations are underway to test the usefulness of providing continuous cutaneous cues for orientation (Raj, McGrath, Rochlis, Newman, & Rupert, 1998) and determine whether they are more resistant to distraction by competing visual tasks (Raj, Kass, & Perry, 2000).

Despite the likely importance of SD to LSA, the obvious overlap in these two concepts, and the similar pattern of mishap findings for SD and LSA investigations, little explicit overlap occurs in the literature concerning these two concepts or in the training that aviators receive. Much of the SD literature does not discuss the nature of the relationship between SD and LSA, although there are several notable exceptions (Benson, 1988; Gillingham, 1992; Cheung, Money, & Sarkar, 1996). The situation is no better in the SA literature, despite the fact that the SA literature describes a theoretical concept that appears to encompass SD (Benson, 1988). For example, a recent book on SA edited by Endsley & Garland (2000) is very informative about SA, but does not include index entries for any of the following terms: "orientation," "disorientation," "spatial orientation," "spatial disorientation," "vestibular," "acceleration," "motion," "position," "force," "G-force," "illusion," or "vertigo." The 383-page book contains indexes for four pages concerning "spatial abilities," but none of these pages is directly pertinent to spatial disorientation vis à vis the surface of the earth or the direction of Earth's gravity vector. Finally, none of the aforementioned classic vestibular illusions are mentioned in the Endsley and Garland book. It should be noted that the book by Endsley and Garland is well worth reading; this example is provided merely to illustrate the apparent lack of communication occurring between researchers specializing in SD and those specializing in LSA. Any number of SA or SD books could have been offered to illustrate the same point.

At times, the lack of communication between different groups leads to confusion, as was mentioned early on by Benson (1988), who noted that the advent of the concept of LSA "has led to a certain clouding of the distinction between spatial disorientation and loss of SA, of which one example is the adoption by some aircrew of the phrase 'loss of situational awareness' as a euphemism for 'spatial disorientation.' " Unfortunately, the years since 1988 have not erased the confusion between SD and LSA. This fact is exemplified by the CFIT Education and Training Aid (Flight Safety Foundation, 1996), which covers most aspects of CFIT thoroughly, but without making any discernable mention of SD. However, the CFIT Education and Training Aid lists the two basic causes of CFIT as "lack of vertical position awareness" (page 3.8) and "lack of horizontal position awareness" (page 3.8), both of which are said to involve the loss of situation awareness by the flight crew. This statement is most likely true, but fails to specify that vertical and horizontal position awareness are central to the concept of spatial orientation and its converse, SD. A more specific description of the CFIT problem would enhance the transition of SD-related knowledge to help persons at risk of CFIT.

When phrases such as LSA and CFIT are used in the aerospace literature concerning experimental research and accident investigation, care should be taken to use them in ways that will clarify the issues and avoid confusion with SD. In years past, the aerospace community came to realize that "pilot error" was not a sufficiently specific description of the cause of a plane crash. Now we must avoid the temptation to consider our job complete when we have identified some general human psychological state as the cause of an accident. As Lyons et al. (1994, page 152) have said concerning SD mishaps: "…if both an attention deficit and SD are part of the chain of events leading to an accident, each should be separately identified as a causal factor if elimination of either would have prevented the accident." This advice makes very good sense in the short term. In the long term, what is needed is to incorporate separately tabulated factors into a model that can accurately predict the amount of variance accounted for by each factor contributing to human error in flight. This requires an initial commitment to differentiate factors that usually get lumped together *a priori*.

To avoid the problem of reification, the lumping of multiple causal factors for human error under one theoretical construct name should not be attempted until sufficient data justify it. At present, SD and LSA can be defined, but many questions remain concerning each theoretical construct and the relation of the respective constructs to one another. For example, while the psychophysics of SD has been explored extensively (Guedry, 1974), there is no validated scale for assessing the experience of spatial orientation/disorientation and no formal establishment of the underlying cognitive dimensions (e.g., confirmation that visual and vestibular dimensions emerge while geographic dimensions do not). While there are scales for measuring SA, it is not clear to the authors how closely the dimensions that have emerged from existing SA scales (such as Taylor's 1990 scale) should match the three-part definition of SA (perception, comprehension, projection) as forwarded by Endsley (1988) and used to classify mishaps by Jones and Endsley (1996).

There have been a few attempts to distinguish SD from LSA as mishap contributors. Gillingham (1992) summarized 633 Class A Aircraft mishaps in the U.S. Air Force from 1980-1989 (Table 1, by permission). During this period, 356 mishaps were "operations related," 81 mishaps were classified as SD-related and 263 as LSA-related; however, there were 270 mishaps where SD and LSA were both mentioned as contributing factors. (Note that the aforementioned categories are not exclusive and hence do not add up 633, personal communication, Previc, 2002). We can infer from the earlier data of Gillingham that 43% (270 SD/LSA mishaps ÷ 633 total mishaps) of U.S. Air Force category A mishaps were SD/LSA related, while 30% [(270 SD/LSA mishaps – 81SD mishaps) ÷ 633 mishaps total] were related to LSA in the absence of SD.

Table 1. 1980-1989 USAF Class A Aircraft Mishaps – as Categorized by Safety Investigation Boards (From Gillingham, 1992, used by permission of the Journal of Vestibular Research)

	Total	Operations related	SD related	LSA related	SD/LSA related
Mishaps	633	356	81	263	270
Fatalities	795	515	115	425	437
Cost (U.S. $)	4,452M	2,558M	539M	2,012M	2,045M

Cheung and colleagues analyzed SD-related accidents (Cheung, Money, Wright, & Bateman, 1995) and LSA events (Cheung, Money, & Sarkar, 1996) in the Canadian forces. Cheung, Money, Wright, & Bateman (1995) collected 154 accident reports across category A, B, and C. They found that 14/62 (23%) of category A accidents had SD as a possible causal factor during the period 1982-1992; SD was unrecognized by the aviator in all but two of the 14 accidents, and two of the accidents appeared to be of vestibular origin (involving the somatogravic illusion). In a separate study of LSA, Cheung, Money, & Sarkar (1996) looked at class A, B, and C (U. S. Naval Flight Surgeon's Manual, 1991) accidents and incidents from 1982-1993, finding that 64 accidents were related to LSA without SD. Of these, three were category A accidents. Hence, 5% of accidents involving LSA without SD were severe enough to be classified as category A. Collectively, the data of Gillingham and of Cheung and colleagues suggest that SD and LSA are much more likely to be present together in a serious accident than is LSA in the absence of SD.

Vestibular Effects Other Than Spatial Disorientation

In addition to the aforementioned ambiguities concerning how the vestibular aspects of SD contribute to LSA and CFIT, there is a notable gap concerning how vestibular effects other than SD contribute to LSA and CFIT. The authors believe that a conceptual model of the vestibular influences upon LSA and human error should include more than vestibularly-mediated SD. Other problems associated with acceleration stimuli include extreme discomfort and distraction caused by nausea and vomiting, decrements of postural equilibrium, decrements of motor coordination, problems with visual performance, and problems with arousal, concentration, and motivation (such as occur during the sopite syndrome, first described by Graybiel & Knepton, 1976). A complete approach to the study of acceleration-induced human error should assess all these aspects of human functioning, so that the relative contribution of each aspect can be understood (Kennedy, Stanney, & Lawson, 2000).

At present, the implicit conceptual model of SD versus LSA is quite simple. If a group of concerned aerospace researchers was asked to encapsulate (via a Venn diagram) the role that vestibular acceleration stimuli play in eliciting LSA and human error, they would probably tend to distinguish acceleration-related contributors to LSA (such as the type of SD known as "the leans") from non-acceleration contributors to LSA (such as increased distraction or decreased concentration). They would also surely separate predominantly "vestibular" SD illusions from predominantly "visual SD illusions, allowing significant overlap for the fact that many cases of SD involve effects of both vestibular and visual origin. This simple conceptual model is diagrammed in Figure 1 (Note that the relative size of different circles does not reflect their relative importance).

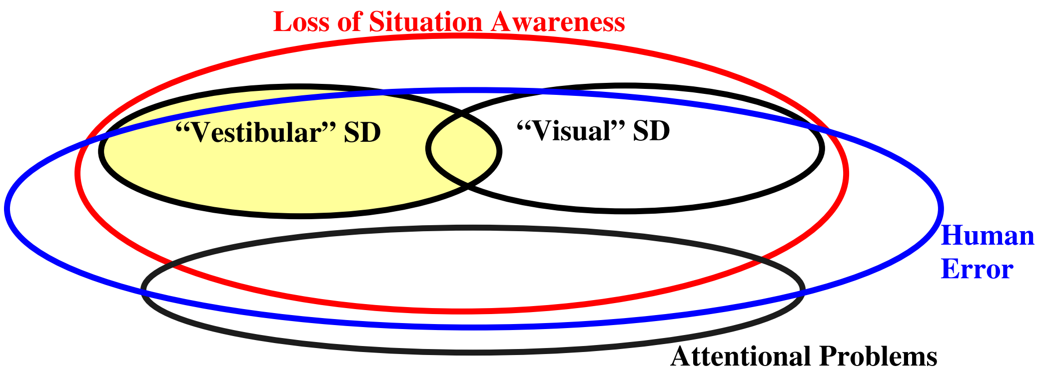

Figure 1. Two-Dimensional Venn Diagram of the Common Conception of the Role Vestibular and Visual Stimuli Play in Eliciting SD, LSA and Human Error in Flight. (Red = LSA; blue = human error, light Yellow = SD of predominantly vestibular origin.)

In Figure 1, SD can be of vestibular, visual, or combined vestibular-visual origin. SD is viewed as a subset of LSA (i.e., if one has SD, one must have a LSA, but not vice versa) and SD intersects with human error (i.e., one can have SD with or without committing an error). LSA also intersects with human error, because one can have LSA with or without committing an error. LSA intersects with attentional problems (e.g., insufficient arousal, poor concentration), but no direct link is envisioned between the vestibular stimuli and decreased attention or alertness. The simple model in Figure 1 would allow an investigator to correctly categorize "the leans" as a type of SD that fosters LSA primarily due to the misleading acceleration stimulus to the vestibular (and somesthetic) receptors, while also acknowledging that visual illusions can cause other forms of SD. However, Figure 1 leads to the conclusion that SD is the only significant means by which acceleration stimuli to the vestibular organs can disrupt human well-being and trigger LSA. This is unlikely, since acceleration stimuli to the vestibular organs probably influence attentional resources, and hence, SA (Graybiel & Knepton, 1976; Lawson & Mead, 1998). While SD is probably the most important way in which vestibular stimuli give rise to LSA and human error during flight, the authors believe it would be a mistake to conclude that

SD is the only way that acceleration stimuli to the vestibular organs contribute to LSA and human error. Rather, we feel that SD of vestibular origin is merely a subset of all vestibular effects that can interact with LSA and human error, as shown in Figure 2.

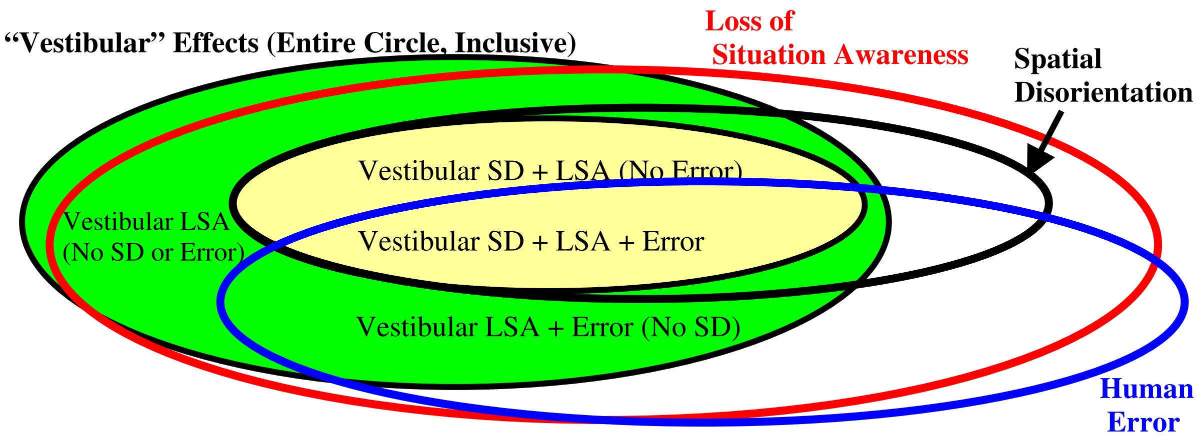

Figure 2. Two-Dimensional Venn Diagram of the Role Vestibular Stimuli Play in Eliciting LSA and Human Error in Flight. (Red = LSA; blue = human error; light yellow = SD of predominantly vestibular origin; green = vestibular effects other than SD.)

Figure 2 diagrams the possible ways that vestibular stimuli can contribute to LSA and human error. Figure 1 assumptions are preserved (in Figure 2) concerning vestibular SD as a subset of all SD and all SD as a subset of LSA. The key point for discussion is that Figure 2 hypothesizes the existence of vestibular effects other than (vestibular) SD, contributing to LSA and human error. Hettinger, Kennedy, and McCauley (1990) carried out an excellent review of the effects of motion upon human performance. They surveyed 33 studies carried out in operational and laboratory environments, noting the reported decrements of performance. Numerous motion-induced problems were noted that do not necessarily imply the presence of SD, including decrements in tests of stance, gait, postural disequilibrium, general activity level, head turning time, choice reaction time, tracing, needle threading, the spoke test (a measure of eye-hand coordination), grip strength, hand steadiness, visual tracking, critical tracking, visual acuity, single letter searching, time estimation, complex counting, mathematics, vigilance (visual and auditory), auditory monitoring, logical inference, grammatical reasoning, navigation plotting, cryptographic encoding/decoding, code substitution, and a combination lock test. Many of the aforementioned tests reflect operationally relevant aspects of in-flight SA that bear little direct relationship to the perception of one's orientation vis à vis gravity and the Earth's surface (e.g., tests reflecting general state of arousal). Other tests (e.g., of navigation or visual performance) should bear some relation both to general orientation (spatial and geographic) and SA, without being within the specific purview of either concept. Finally, some tests (e.g., of manual coordination) may reflect vestibular/somesthetic influences on in-flight performance that do not directly reflect SD or SA. Clearly the interactions among vestibular effects, LSA, and human error are much more complicated than usually implied in the literature. It is likely that the interactions among visual effects, LSA, and human error are at least as complicated. This leads to a dramatically expanded conceptualization of the role vestibular and visual effects play in LSA and human error, as diagrammed in Figure 3.

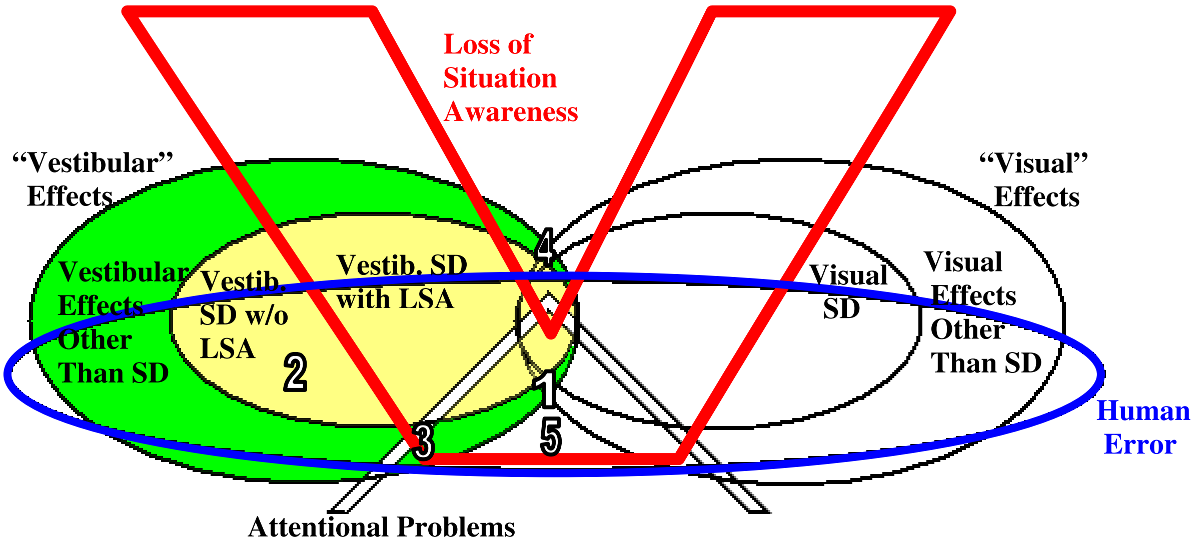

Figure 3. Two-Dimensional Venn Diagram of a More Comprehensive Conception of the Role Vestibular and Visual Stimuli Play in Eliciting LSA and Human Error in Flight. (Red = LSA; blue = human Error; green = vestibular effects other than SD; yellow = vestibular SD; numerals are explained in text.)

In this more comprehensive conception, vestibular SD is viewed as one aspect (subset) of vestibular effects and general vestibular effects can foster LSA in ways other than producing SD. Distraction and loss of concentration are viewed as problems that can arise either separately from vestibular effects or because of cognitive changes triggered by vestibular effects (including vestibular SD, motion sickness, or sopite syndrome). As denoted by numeral 1 in Figure 3, combined vestibular and visual effects can foster LSA without necessarily producing SD, by degrading dynamic visual acuity (Guedry, Lentz, & Jell, 1979). The fact that vestibular effects are a superset of vestibular SD fits the observation that certain disorienting head movements made during rotation or in high-G environments (Lackner & Graybiel, 1987) are also known to be quite sickening. Numeral 2 of Figure 3 shows that SD might be identified as a contributor to a human error (leading to a mishap) without LSA also being implicated, as one can infer (personal communication, Previc, 2002) happens in 7 of the SD-only mishaps that remain when one subtracts the 263 LSA mishaps from the 270 combined SD/LSA mishaps shown in Table 1 of Gillingham, 1992 (See Table 1 of this paper). Numeral 3 in Figure 3 represents the sopite syndrome (Graybiel & Knepton, 1976; Lawson & Mead, 1998), shown in this case as intersecting with attentional problems, LSA, and human error). Figure 3 allows for combined visual and vestibular effects to be produced without causing LSA or human error, as might occur upon changing one's glasses prescription, wherein subtle changes in one's vestibulo-ocular reflex may take place. Such benign visual-vestibular effects are denoted by numeral 4. Finally, Figure 3 allows for LSA to contribute to human error without vestibular, visual, or attentional factors being involved, as denoted by numeral 5.

Despite the fact that Venn Diagram in Figure 3 is geometrically complex, there are still numerous simplifications present. For example, the role of geographic disorientation is not depicted. Also, Figure 3 fails to acknowledge that purely cutaneous and kinesthetic mechanisms may produce LSA and human error or combine with vestibular influences. Finally, the reader should note that Figures 1, 2, and 3 represent conceptual models regarding the relative domain of different contributors to SD, LSA, and human error; the authors have not complicated these conceptual models of proximal causal factors for human error by explicitly incorporating the broad classification levels used to categorize incident and mishap outcomes. Hence, the authors have not attempted to depict how type 1 (unrecognized), type 2 (recognized), and type 3 (incapacitating) SD and type 1 (perception), type 2 (comprehension), and type 3 (projection) LSA levels fall into the models shown in Figures 1-3. Nevertheless, the reader should have no trouble guessing that type 1 (unrecognized) SD mishaps fall under "vestibular SD + LSA + Error," as shown in Figures 2 and 3. The task becomes more difficult after this point, however.

A. Vestibular Effects Other Than SD: Motion Sickness and the Sopite Syndrome

The oldest and most obvious way in which vestibular stimuli may foster decreased performance, human error, or LSA is via elicitation of the nausea syndrome. The nausea syndrome includes such signs and symptoms as nausea, retching, vomiting, cold sweating, and increased salivation. The nausea syndrome is most closely associated with travel by sea, where seasickness has created widespread operational challenges for many centuries. Pethybridge (1982) found that 70% of Royal Naval personnel are susceptible to episodes of sea-sickness (especially in rough seas or smaller ships), and that 80% of the sufferers felt they had some difficulty working on days when they felt ill (the most susceptible said they had extreme difficulty working). In the US Navy, the Naval Medical Information Management Center (1996) estimates that over 40,000 new cases of "motion intolerance" per year were recorded between 1980-92. Schwab (1943) studied 115 U.S. Naval personnel who had been hospitalized for chronic seasickness. His clinical assessment indicated that the worst-affected among these personnel were only capable of about 40% of their normal land efficiency even on large vessels, while on medium or small vessels they operated at 5-10% of their land efficiency.

Wiker and Pepper (1978) tested six U. S. Coast Guard personnel aboard a patrol boat (1978); they noticed a general decrement in six of eight performance tasks during the first steaming day. However, only three tasks (grammatical reasoning, single letter searching, and critical tracking) were degraded enough to be statistically significant for the sample obtained. Using similar tests, Wiker, Pepper, and McCauley (1980) tested three groups of six volunteers in three different Navy vessels, finding that performance on all nine measures (drawn from a battery of six tests) was significantly poorer in the patrol boat than in the other two vessels or when compared to baseline tests at the dockside. Also, motion sickness in the patrol boat overwhelmed any practice effect in performance, as was observed in the two less-sickening vessels during repeated performance testing at sea. The complex tasks were most adversely affected by motion, as were those requiring periods of sustained performance or those that allowed the subjects to control the pace of their efforts.

Some people are affected by sea travel even after returning to land; Gordon, Spitzer, Doweck, Melamed, & Shupak (1995) found that "landsickness" can strike persons of widely varying susceptibility after a sea voyage, resulting in feelings of postural instability and perceived instability of the visual field during self-movement. Similar effects have been noted following space flight (Nicogossian Huntoon, & Pool, 1989) and simulator use (Gower, Lilienthal, Kennedy, & Fowlkes, 1987). However, there is some reason to believe that postural disequilibrium aftereffects of simulator exposure may implicate disorientation mechanisms, not just those mechanisms involved in motion sickness (Kennedy, Berbaum, & Lilienthal, 1997). Moreover, postural disequilibrium is of less concern during flight operations, where the personnel directly in control of the aircraft are seated and restrained. For these reasons, postural disequilibrium will receive less emphasis in this paper.

In the aviation setting, motion sickness affects students and navigators most strongly, occasionally causing personnel to become prostrated by sickness and unable to perform their duties (Benson, 1988; Lawson, Mead, and Clark, 1997; Kay, Lawson, & Clark, 1998). Guignard and McCauley (1990) note that flying performance in rough air is generally maintained; however, they point out that additional physiological cost is required to maintain performance at pre-flight levels. The concept that additional resources must be tapped to keep performance level steady under situations of stress is a common one, having been applied to studies of fatigue and sleep deprivation (Hockey 1997; Hardy, 1999

There is little direct evidence concerning the affect of nausea on aerospace operations, but cases have been documented by Reason and Brand (1975) wherein nausea and vomiting have delayed planned American space operations (e.g., extravehicular activity) by several hours, disrupted planned work/rest duty cycles, imposed voluntary self-restrictions upon physical activity (especially head movement), and may have contributed to the early termination of a Soviet space mission. Reason and Brand (1975) described space sickness among the three crewmembers of Skylab III, noting that during the first two days of the mission, the crewmembers had to slow down their planned activities, restrict movement around the space station, and lie down to rest during the workday. A similar tendency to limit head movements was seen in Spacelab 1 astronauts (Oman, Lichtenberg, & Money, 1990), who attributed their space sickness directly to the level of physical activity demanded of them during the early part of the mission and believed they might have been able to avoid vomiting had they been allowed to delay the completion of their activities during their first days in space. Impairments of mood, feelings of increased workload, and disturbances of tracking performance were noticed (Manzey, Lorenz, & Poljakaov, 1998) during the first three weeks of a cosmonaut's stay in space, after which time his mood and performance stabilized.

The relationships among nausea, vomiting, and performance are complicated. While it is obvious that a person cannot be doing his or her job while engaged in vomiting, it does not necessarily follow that the individuals most likely to vomit will be the worst performers. Wendt and colleagues (Alexander et al., 1945; Alexander et al., 1955; Johnson & Wendt, 1964) did a series of studies using a vertical oscillation stimulus. They found that in seven of eight performance tasks, the performance of those who did not vomit was worse than those who vomited. (However, duration of exposure was not constant between the two groups.) The tasks that seemed to be most affected following exposure were mirror drawing and code substitution.

The Naval Safety Supervisor (1993) warns safety personnel that motion sickness can weaken, distract, or disorient people and that it is dangerous because is causes a loss in normal alertness and decision-making abilities, which can cause a person to make serious mistakes. Studies in various motion settings suggest that vestibular stimuli cause changes in cognitive or affective state (Lawson & Mead, 1998) that should affect SA adversely. Even mild and non-sickening vehicle motions have been associated with relaxation, drowsiness, fatigue, decreased concentration, and decreased motivation (Lawson, Kass, Muth, Sommers, & Guzy, 2001). Such effects have been collectively referred to as the sopite syndrome (Graybiel & Knepton, 1976; Lawson & Mead, 1998). For example, a senior chief petty officer in the U.S. Navy (anonymous personal communication to first author, 1998) with extensive experience at sea reported that despite being essentially immune to nausea at sea, he had often experienced overwhelming drowsiness and fatigue during the first few days of leaving harbor, whenever he had been off the ship for any extended period of time. He related an event where he was standing watch aboard ship during Desert Shield in a slow, steady sea that he found overwhelmingly sedating. He felt that in this particular case, his fitness for duty might have been compromised.

Sopite syndrome may affect some individuals profoundly. For example, a young Navy flight surgeon (anonymous personal communication to first author, 1998) related the case of an individual he knows who often finds it impossible to stay awake while riding in a car. The person often falls asleep, even while driving, and has wrecked two cars in this manner. This person does not seem to suffer from these spontaneous sleeping spells at any time when he is not in a moving situation.

Such curious experiences may be partially attributable to the motion stimulus. A large survey conducted during NATO Atlantic Fleet Operations (Colwell, 2000) asked personnel about dozens of performance problems encountered at sea. They found that the most frequently mentioned complaints were fatigue and poor sleep quality. These findings were related to ship size and sea state, being worse for small ships or increased wave motion.

According to Guignard and McCauley (1990), motion sickness can elicit lassitude, yawning, and disinclination to be active. They state that such effects which can be serious in operational situations, occasionally leading to the abandonment of performance of even critical tasks. They also point out that continuous oscillatory motions during rough seas can impair cognitive performance in a cumulative way and affect the quality of sleep and wakefulness, even among persons who are not seasick. The many factors contributing to fatigue at sea can progressively degrade and delay the work of the ship's departments, which can, in turn, reduce morale (Guignard & McCauley, 1990).

However, it is not common for motion sickness to lead to the abandonment of critical tasks. The more common outcome is that a sick person can rally and perform when the need is great enough, such as in an emergency (Reason & Brand, 1975). Birren (1949) proposed a useful distinction between peak efficiency and maintenance efficiency. He suggested that while peak efficiency (such as needed during an emergency) is likely to be unaffected by seasickness, maintenance efficiency for routine tasks may suffer during rough weather, with the crew losing interest in doing anything except the bare necessities and spending most of their free time in their bunks. Subjects in a laboratory study by Reason and Graybiel (1969) spent most of their free time in bed during a 3-day adaptation experiment within a rotating room. The onboard observer noted that even after their relatively minor initial disturbances subsided, the three subjects sought every opportunity for rest. Subjects were notably lethargic, often sleeping 12 hours or more.

There are almost no studies assessing performance during sopite syndrome. In one such study, Wright, Bose, and Stiles (1994) observed worse digit-span test performance among nauseated individuals (n=26) following helicopter flight. However, the experimenters also observed worse digit-span test performance when participants had symptoms indicative of sopite syndrome and nausea was not prominent.

Sopite syndrome may affect communication profoundly. Graybiel and Knepton (1976) noted their subjects were detached, distant, less communicative, and less willing to engage in group behavior. Such an affective state could hinder good communication, crew coordination and group SA during flight operations. Space Adaptation Syndrome has already been suggested as a factor hindering communication between ground and space crews (Kelly & Kanas, 1993).

Hettinger, Kennedy, & McCauley (1990) categorized human performance into four basic processes, using the approach of Christensen and Mills (1967, ref 17, from HKM, from Crampton). The processes were mediational, communicative, perceptual, and motor. Of these, Hettinger and colleagues noted that while good communication is required in almost all conditions where humans experience vehicle motion, this remains an aspect of motion sickness that has not received attention. This seems an area ripe for exploration, considering that communication is a vital ingredient in teamwork and the notion of team situation awareness has been discussed (Prince & Salas, 2000).

B. Vestibular Effects Other Than SD: Motion-Induced Degradation of Visual Acuity

Another important way in which certain acceleration stimuli can disrupt human performance is by making the world harder to see. Visible nystagmus (eye beating) is one of the earliest signs noted when a person is challenged by certain kinds of motion stimuli (Reason & Graybiel, 1970). Such nystagmus can degrade one's ability to interpret visual displays, which is a critical component of SA. Nystagmic responses can also be among the most persistent of aftereffects following adaptation to a motion stimulus, in some cases lasting for weeks (Guedry, 1965).

Visual acuity is commonly measured by having a stationary person read a stationary eye chart. However, visual performance is highly dependent upon one's ability to see moving objects clearly and upon one's ability to see clearly while one's head is moving through space. To view objects clearly, one must keep them steady on the retina, regardless of whether the object or the observer is moving;

this is accomplished by two eye-movement reflexes: the pursuit reflex and the vestibulo-ocular reflex. The pursuit reflex is visually mediated, using information about error of visual fixation to generate corrective eye movements that keep the visual target foveated (Stott, 1988). The vestibulo-ocular reflex uses vestibular information about head motion to generate corrective eye movements that stabilize the eyeball in space during self-movement. If the display undergoes angular oscillation about the stationary subject, the pursuit reflex will keep up with the display until approximately 1Hz display vibration frequency (Stott, 1988). However, if the subject's body is oscillated in reference to a stationary display, the vestibulo-ocular reflex will maintain gaze stability at least up to 8Hz. (Stott, 1988).

A special challenge to visual acuity occurs when an individual and a display move together through the world in a yoked fashion (Lawson, Rupert, Guedry, Grissett, & Mead, 1997), such as occurs inside a moving vehicle with internal displays. For certain combinations of acceleration and deceleration (Guedry, Lentz, Jell, 1979; Guedry, Lentz, Jell, & Norman, 1981), the vestibulo-ocular reflex will no longer be helpful in reading the head-fixed display, because it will generate eye-movements that stabilize the eye in respect to external space, but jiggle the eye in reference to the self-fixed display. For example, in the oscillation paradigm of Guedry, Lentz, and Jell (1979), the visual angle required to sustain clear visual acuity increased 2-5 times over normal. Such a dramatic visual degradation could have profound consequences for SA in flight, where critical information is obtained from visual displays.

C. Vestibular Effects Other Than SD: Fainting

A final vestibular effect of motion that is not usually discussed is fainting. Feeling faint, dizzy, or light-headed is a common reaction to unusual motions even at low G-levels (Bittner, Gore, & Hooey, 1997; Lawson, Graeber, Mead, & Muth, 2002). The physiological changes associated with fainting are sometimes seen in subjects exposed to motion experiments (Sunahara, Johnson, & Taylor, 1964; Reason & Brand, 1975; Sunahara, Farewell, Mintz, & Johnson, 1987; Sachanska, 1996; Cheung & Hofer, 2001). The authors of the present paper conjecture that only a very few people will faint outright in response to unusual motion, but for those who do, all SA has been forfeited until recovery.

Conclusions and Recommendations

It is widely known that vestibular stimuli can contribute to LSA and human error via the elicitation of SD. This paper presented evidence to warrant further exploration of the idea that vestibular effects can affect SA and human performance without necessarily triggering SD. Vestibular effects other than SD are associated with motion sickness, sopite syndrome, motion-induced loss of visual acuity, and motion-induced fainting. These various effects could potentially affect each of the three levels of SA, including perception, comprehension, and projection. Numerous examples exist of motion-related performance decrements that should be relevant to SA.

Restricting consideration solely to specific motion-related performance decrements demonstrated to be statistically significant in <u>multiple</u> studies (as reviewed by Hettinger, Kennedy, & McCauley, 1990), one can conclude conservatively that the most robust decrements following vestibular stimuli appear for tests of balance (standing and walking), critical tracking, navigation plotting, and time estimation. Of these four, only postural disequilibrium could not be called an in-flight vestibular effect that is distinct from SD. Critical tracking (Jex & Phatak, 1966), which entails manually tracking (or compensating) for a visual object that is moving unpredictably, is a psychomotor task that is clearly relevant to aviation (Blower, Albert, and Williams, 2000). The finding that navigation skills are disrupted by vestibular stimuli is very interesting, because vestibular illusions that lead to SD are considered quite distinct from geographic disorientation, or "getting lost." Yet, in Hettinger, Kennedy, and McCauley's 1990 review, we see that vestibular stimuli can disrupt certain aspects of navigation. Hence, it is conceivable that vestibular stimuli could indirectly disrupt the maintenance of good geographic disorientation.

Perhaps the strongest finding from Hettinger et al. (1990), and the one deemed by them to be least susceptible to confounding influences (such as biodynamic effects or variations in individual coping) was the observation that normal subjects perceive the passage of time less accurately while adapting to a slowly rotating room or to space flight, while subjects without a functioning vestibular labyrinth report no such effects. This is interesting, because time is an important aspect of SA (Endsley 2000). Endsley (2000) points out that individuals must constrain their limited attentional resources to the most important aspects of the situation in order to maintain SA, and that they do so partly by understanding how much time is available until some event occurs or some action must be taken. Hence, it would be interesting to determine if the known effect a vestibular stimulus can have upon temporal estimation will also be reflected by measures of SA.

The authors recommend that the relationship between aspects of SA and certain vestibular effects should be explored in the laboratory and in moving vehicles. Firstly, when a case of LSA involves a failure to perceive available cues concerning one's spatial position, the link to SD should be explored. Secondly, when a case of LSA involves a failure of attention or vigilance, the possible link to sopite syndrome should be explored. Finally, vestibular effects and LSA may intersect in cases where there people have trouble extracting needed information from head-fixed visual displays, manually tracking moving visual targets, navigating, or estimating temporal aspects of the situation. Of course, these various vestibular effects may interact with one another as well as with LSA.

Vestibular stimuli may contribute to human error in vehicle operations in ways that are seldom considered. It is not current practice for laboratory scientists who study the effects of sleep deprivation, workload, or LSA to consider their findings as potentially modified by the acceleration stimulus that occurs during most vehicle operations. Moreover, it is not current practice for scientists conducting sleep deprivation, workload, or LSA experiments inside moving vehicles to collect vehicle accelerometer data and see how it covaries with the phenomenon of interest. Since vestibular stimuli during military vehicle operations can make it more difficult to stay spatially oriented, more difficult to stay alert, more difficult to stay motivated, more difficult to read displays, more difficult to coordinate manual activity, more difficult to track targets, and more difficult to estimate time, then the authors conjecture that the acceleration stimulus to the subject is not merely a concern for spatial orientation researchers, but for all researchers interested in human performance during vehicle operations.

The current approach views human error in aviation as a phenomenon that is partially mediated by vestibular mechanisms, via the production of SD. However, the current approach treats all other vestibular effects of motion as independent of human error in aviation. Instead, we should widen our scope of assessment to include more than one or two dependent measures at a time; we should measure SD, LSA, motion sickness, sopite syndrome, postural disequilibrium, manual dexterity, visual acuity and time estimation <u>together</u> when feasible, so a true understanding can be gained of the relative contribution of each to a human's performance outcomes (Kennedy, Stanney, & Lawson (2000).

If the concepts encompassed by the phrases SD and LSA are to coexist meaningfully and be applied appropriately in the future, much work will be necessary to confirm that they represent necessary and consistent constructs, to determine their dimensions, and to understand their points of convergence and divergence. Without such basic research, our attempts to understand the mental state that contributes to most accidents will be confused by ill-characterized concepts whose relations are unknown.

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The Effects of Helmet-Mounted Display Symbology on the Opto-Kinetic Cervical Reflex and Frame of Reference

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Summary

Spatial disorientation (SD) accidents are a major contributor to the Class A mishap rate in the US Air Force. A recent investigation showed that transitions between visual meteorological conditions (VMC), when pilots use real-world visual cues to fly, to instrument meteorological conditions (IMC), when pilots have to use instruments to fly, were a leading cause of SD. In VMC, the true horizon is the primary visual cue pilots use to orient themselves. In IMC, pilots must rely on a representation of the horizon as their primary visual cue to maintain spatial orientation. Research has shown that when pilots fly in VMC, they tilt their heads in the direction opposite that of aircraft roll in an effort to keep the horizon fixed in their visual field. This implies that pilots use a world frame of reference for determining orientation. However, pilots do not tilt their heads in IMC when viewing the horizon symbol on a head-down, aircraft-referenced attitude indicator. Because pilots must transition between these two frames of reference when transitioning between VMC and IMC, this may be causing SD. The helmet-mounted display (HMD) is currently being tested as a means of displaying attitude information. The HMD symbology tested portrays a *conformal* horizon symbol which overlays the true horizon. In VMC, pilots see the true horizon and the conformal horizon symbol simultaneously. In IMC, pilots see only the horizon symbol. It was hypothesized that pilots would tilt their heads in VMC and in IMC (due to the fact that the conformal horizon represents the true horizon). Eleven pilot-subjects completed a VMC and an IMC flight task. Results showed no *practical* head tilt in either task. This was attributed to the nature of the task. Task demands determine the visual information to which pilots attend. This attention narrowing may influence the strength of the OKCR.

Introduction and Background

A recent survey of Class A mishaps occurring in 1994-1998 showed that 27% of these mishaps involved SD (Neubauer, 2000). A recent interview conducted to classify different types of SD showed that 63% of all pilots surveyed noted that the lack of a visual horizon was one of the most common contributors to SD (Sipes and Lessard, 2000). Because the horizon is the primary visual cue pilots use to orient themselves in flight, it follows that SD occurs when the horizon is not present. In VMC, pilots use the true horizon to orient themselves. In IMC, pilots must use a representation of the horizon to orient themselves. The traditional head-down instrument used for orientation is the attitude indicator (AI) and it is an aircraft-referenced display. This means that the aircraft symbol stays fixed in the center of the display and the horizon moves about it to represent aircraft attitude. The concept that attitude instruments should have an aircraft frame of reference was accepted because it was thought that pilots maintained alignment of their head and body with the aircraft. In this case, pilots are using the aircraft as their frame of reference within which they maintain their head position. Since the frame of reference is seen as fixed, the aircraft is perceived as the fixed part of

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the scene and the horizon is seen as the moving part of the scene – an aircraft frame of reference (DeHart, 1985; Weintraub and Ensing, 1992).

In 1973, Hasbrook and Rasmussen documented a head-horizon tilt phenomena that refuted the original assumption of pilot head alignment within the cockpit. They observed pilots tilting their heads to a position normal to the real horizon when making shallow and medium-banked turns during ground-oriented maneuvers. In 1989, Patterson also found that pilots were tilting their heads during visual maneuvers. Figure 1 shows the difference between the head orientation assumed of pilots in flight and the observed head

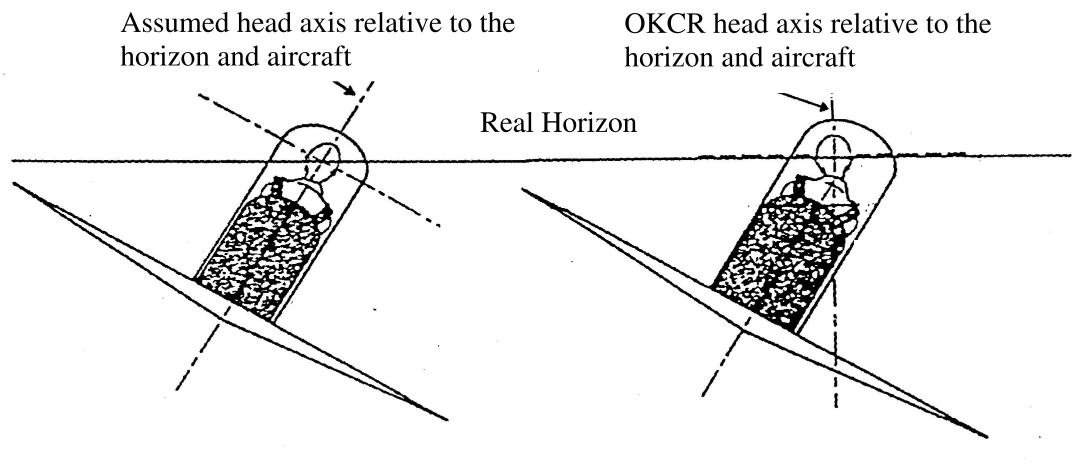

Figure 1. Head Orientations (Hasbrook and Rasmussen, 1973).

position of pilots in flight. Hasbrook and Rasmussen (1973, p. 15) speculated that "man prefers to keep his eyes normal to his visual environment". This observation makes sense because previous research has found that people naturally use the horizontal as a norm for judgment (Takala, 1951). The fact that pilots tilt their head in flight has two strong implications. First, although it was generally accepted that pilots viewed the world as stationary and the aircraft as moving when using real-world visual cues (Gillingham and Wolfe, 1985; Grether, 1947; Roscoe, 1992), this head tilt observation provides evidence for that theory. Second, the underlying assumption (pilots keep their head upright) driving the design of attitude indicators is inaccurate.

Patterson (1995, 1997) studied the phenomena more thoroughly and documented the occurrence of a visual response he termed the opto-kinetic cervical reflex (OKCR). The response causes pilots to subconsciously align their heads with the horizon. He attributed the head tilt to pilots trying to maintain a clear retinal image of the horizon while the aircraft maneuvered (Patterson, 1995, 1997). Patterson hypothesized that pilots use the horizon as their primary visual cue for determining orientation.

When pilots flew in VMC, Patterson found that pilots were tilting their heads in the opposite direction of aircraft roll, thus keeping the horizon stable on their retinas and a fixed point in their reference frame. When pilots flew in IMC (using an attitude indicator as their head-down attitude instrument in this study), no head tilt was recorded. Therefore, Patterson deduced that making a transition between the two visual cues also caused a transition in frames of reference. This switch in frames of reference causes a switch in the pilot's mental representation of the world and may be the cause of SD problems.

Since Patterson's work in 1995, additional studies have been conducted which have replicated Patterson's findings and have attempted to better characterize the head tilt response for a variety of tasks and aircraft platforms (Braithwaite, Beal, Alvarez, Jones, and Estrada (1998); Craig, Jennings, and Swail, 2000; Gallimore, Brannon, Patterson, and Nalepka, 1999; Gallimore, Patterson, Brannon, and Nalepka, 2000; Jennings, Gubbels, Swail, and Craig, 1998; Merryman and Cacioppo, 1997; Shimada, 1995; Smith, Cacioppo, and Hinman, 1997). Most notably, Merryman and Cacioppo (1997) were the first to test for and document the OKCR in actual flight. When the head tilt data from the flight test and the simulator studies were compared, there were no significant differences among them. One of the more interesting findings relates to helicopter pilots flying profiles at night using night-vision goggles (NVGs). Braithwaite et al. (1998) conducted a study in a motion-based helicopter simulator and showed that helicopter pilots flying day missions in VMC exhibited significant OKCR. OKCR was also present when flying night missions using NVGs. As long as the true horizon was visible to pilots, regardless of whether it was visible through natural or augmented vision, head tilt occurred. Craig et al. (2000) observed this head tilt response in helicopter pilots when they used head-steered sensors to increase visibility. Jennings et al. (1998) showed the presence of the OKCR in pilots flying helicopters in low-level search and rescue missions. Gallimore et al. (1999) tested the effects of reduced FOV on the OKCR to determine if minimizing the amount of visual scene pilots saw affected the OKCR. There was no significant difference in head tilt for FOVs of 40°, 60°, and 100°. Therefore, as long as a portion (even a small portion) of the true horizon was perceived by pilots, OKCR was in effect. In addition to the military applications, a study was conducted to determine if general aviation pilots also exhibit the OKCR. Shimada (1995) used a Cessna Skyhawk to conduct his study and showed that pilots were indeed tilting their heads in the opposite direction of aircraft bank when flying in VMC.

The constant theme that persists in all of these studies is the compelling nature of the OKCR in VMC flight. The presence of the true horizon seems to be the key to eliciting the OKCR. The research has also shown that the horizon symbol on the AI was not successful in eliciting the OKCR. The newest way of presenting attitude information is via a helmet-mounted display (HMD). The HMD offers a significant advantage over the traditional AI in portraying attitude information in that pilots need not divert their attention from the outside world into the cockpit to determine exact pitch, roll, and yaw information. HMD symbology is focused at optical infinity and because of this, pilots are able to see the real world while viewing pertinent symbology. Also, attitude information on the HMD can be conformal – a symbol displayed on the HMD overlaps with the real-world feature. Therefore, when the real world is not visible, pilots can infer the location of a real-world feature by relying on the location of the symbology representing it.

On the HMD, the horizon symbol moves with the true horizon. Therefore, the HMD symbology is aircraft-referenced, just like the AI. However, unlike the AI, the symbology occupies a wider field of view (FOV), is not compressed, and is conformal with the real world. Although there have been studies conducted in which HMD symbology has been present during a VMC task (Craig et al., 2000; Jennings et al., 1998) there has never been an investigation of the effect of HMD symbology on head tilt in IMC. Therefore, it is unknown whether a conformal horizon symbol will evoke the OKCR.

Since pilots tilt their head when seeing the real world, and the HMD symbology simply exists in synergy with the outside view, one would expect the OKCR to occur in VMC when the HMD is presenting attitude information overlaid on the real world. The question is: Is the conformal HMD horizon symbol compelling enough to cause the OKCR while flying in the clouds? If pilots do tilt their heads during both VMC and IMC flying, this could potentially reduce SD.

Objectives And Hypotheses

One objective of this research was to characterize the OKCR in a VMC flight task with the true horizon present using an HMD portraying on-boresight attitude symbology. Another objective was to determine if the OKCR was also induced by the conformal horizon symbol when pilots flew in IMC using the HMD. The first hypothesis was that pilots would align their heads with the horizon in VMC flight while using the HMD. This is based on the results of the OKCR research thus far. It was also hypothesized that pilots would align their heads with the horizon symbol on the HMD.

Method

Subjects

A total of 11 pilots from Wright-Patterson Air Force Base, Shaw Air Force Base, and Springfield Air National Guard volunteered to participate in accordance with human subject requirements specified by the USAF and Wright State University. Subjects had a minimum of 100 hours of head-up display (HUD) experience.

Apparatus

The research simulator consisted of a fixed-base, single-seat, F-15 type shell with an F-15E stick (mounted on the side as in the F-16), and F-15E throttles (Figure 2). An F-16 aeromodel was employed in the simulator. A single Matsushita 21" by 16" color monitor graphically displays the head-down formats. The research facility also housed three BARCO Retrographics 801 machines that supported a 111° horizontal by 27° vertical out-the-window scene. These machines were 6.5 feet from the design eye-point.

Figure 2. Cockpit Simulator.

A Kaiser SIM EYE 40 HMD system was used to present attitude symbology projected on two combiner glasses positioned in front of the pilot's eyes. The system consisted of a helmet, an HMD, and an electrical interface unit. The HMD was binocular, portrayed monochrome symbology, had a 40° circular FOV with 100% overlap, and had 1280 x 1024 resolution. A Flock of Birds 6-D Multi-Receiver/Transmitter Tracking

Device was attached to the helmet and measured pilot's head position. A head-down display suite consisting of an up-front control (UFC) unit and three 6X8 multifunction displays (MFDs) was provided to the pilots, although the pilots did not have to interact with it to perform the tasks.

The HMD attitude symbology consisted of the MIL-STD HUD symbology set (Figure 3) which remained visible for a 30° horizontal by 20° vertical FOV. This is the FOV of a traditional HUD and was the FOV for the "virtual HUD" on the helmet for this application. The MIL-STD HUD symbology set was chosen for the current study because it includes all information required for instrument flight (U.S. Department of Defense, 1996).

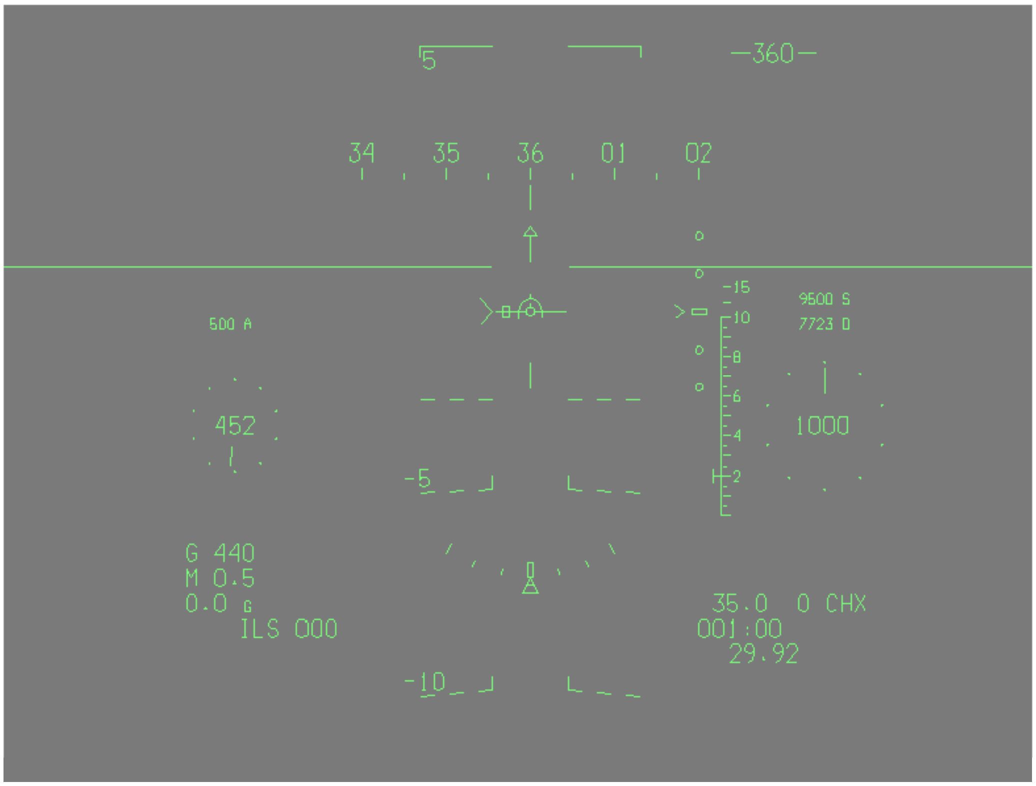

Figure 3. MIL-STD HUD Symbology (U.S. Department of Defense, 1996).

Flight Tasks and Experimental Design

Each pilot performed two tasks for data collection; a VMC flight task and an IMC flight task. The objective of both tasks was to determine if and how much pilots tilted (rolled) their head when flying with outside visual cues while using the MIL-STD HUD symbology on an HMD. In the VMC task, the HMD symbology was projected in front of the pilot's eyes, and the out-the-window scene was displayed on the BARCO projectors. In previous studies, pilots were able to choose their angle of bank to complete the prescribed task. Some pilots did not often roll above 45° - 60°, and the ones who did, did not maintain this angle of bank for a substantial period of time. Because of this, there was high variability in the data for the higher angles of bank. In the current study, an effort was made to get more data at these higher bank angles so as to better characterize the OKCR in this region. Therefore, it was decided to command pilots to certain bank angles for a specified period of time. This was accomplished via verbal instructions to pilots during the task. Pilots were also instructed to maintain a commanded altitude of 12,000 feet mean sea level (MSL) and a commanded airspeed of 400 knots. Head tilt and aircraft roll data were collected at 20 Hertz (Hz).

In the IMC task, instead of portraying an out-the-window scene on the BARCO projectors, the projectors provided a white background to simulate instrument flight conditions. Again, verbal instructions were used to indicate the commanded bank angle. Pilots were also told to maintain a commanded altitude of 12,000 feet MSL and a commanded airspeed of 400 knots. Head tilt data and aircraft roll data was collected at 20 Hz.

The study employed a within-subjects design with one independent variable and one dependent variable. The independent variable, angular aircraft bank (or roll), had 32 levels (80° right bank to 80° left bank in 5° increments). Right bank is represented with positive values and left bank is represented with negative values. The dependent variable was degree of head tilt.

Procedures

Upon arrival, the subjects were briefed on the purpose of the study and procedures for the experiment. After a consent form was signed, a standardized briefing was presented that included safety issues, details of the practice sessions, and details of the data collection sessions. An additional briefing took place once pilots were inside the cockpit, but before the HMD was donned. The mission profiles were described, the HMD was put on, and the HMD symbology was explained.

Pilots received a practice session before each data collection session. The purpose of the practice session was to allow the pilot to become familiar with the aeromodel characteristics and the symbology functionality. Each practice session contained one abbreviated mission profile similar to the data collection profile for that task. A break was offered following the first data collection run. When both data collection tasks were finished, pilots were asked to fill out a questionnaire pertaining to the study.

Results

Task I - VMC Flight Task

Each subject's data file was reorganized via computer software into five-degree categories (-80 to -76, -75 to -71, -70 to -66, . . . , 66 to 70, 71 to 75, 76 to 80) with an average head tilt value for each grouping. The result was an individual subject data file with 32 aircraft roll levels and 32 corresponding head tilt values. Linear regression analyses were conducted to determine the relationship between aircraft roll and head tilt. A check for outliers revealed four data points that were subsequently removed. The analysis showed that there was a significant linear relationship between aircraft roll and head tilt ($F(1,343) = 51.903$, $p = 0.0001$). The regression equation is:

$$\text{Head Tilt} = 0.3651 - 0.00892\ (\text{Aircraft Roll});\ \text{Adjusted } R^2 = 0.13$$

A lack of fit test was also conducted to ensure that the relationship between the two variables was linear. The test showed no lack of fit of the linear relationship ($F(30,313) = 1.09$, $p = 0.3443$). Figure 4 shows the average value of head tilt at each aircraft bank category.

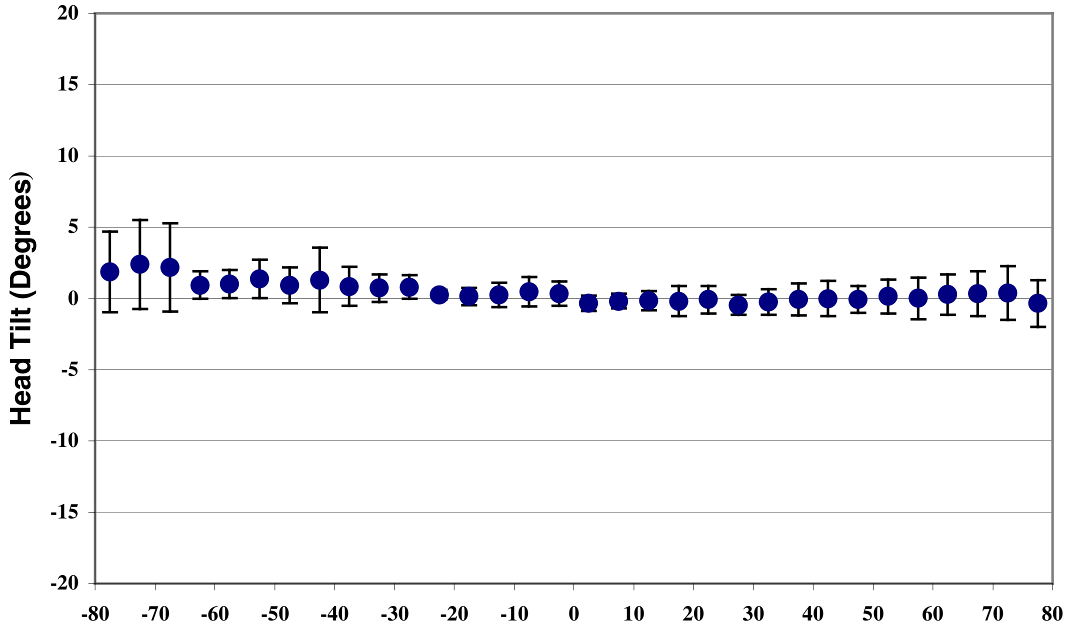

Figure 4. VMC Task – Average Head Tilt (Error bars represent standard deviation).

An analysis of variance showed a statistically significant difference between specific levels of aircraft roll in terms of head tilt ($F(31,313) = 2.74$, $p = 0.0001$), however, the regression analysis verifies that the relationship is linear with a very small slope (0.009) and a maximum head tilt value at $\pm 1.085°$. Based on previous studies, head tilt angles of less than three degrees were considered not to have real world practical significance because of potential aircraft vibration induced head movement, as well as random/natural head movement.

IMC Flight Task

Manipulation of the data for the IMC Task was identical to that of the VMC Task. After checking for outliers and assuring compliance of the linear regression analysis assumptions, the regression analysis showed a significant linear relationship between aircraft roll and head tilt ($F(1,349) = 19.756$, $p = 0.0001$). This linear relationship was confirmed by an insignificant lack of fit test ($F(30,319) = 0.86$, $p = 0.688$). The regression equation is:

$$\text{Head Tilt} = 0.1974 - 0.00375\ (\text{Aircraft Roll});\ \text{Adjusted } R^2 = 0.05$$

Again, the analysis of variance showed a *statistically* significant difference between specific levels of aircraft roll in terms of head tilt ($F(31,319) = 1.46$, $p = 0.0595$), but there is no *practical* significance in head roll angles of three degrees or less. Figure 5 shows the average head tilt for each aircraft bank category.

Discussion

The OKCR has been shown to exist in numerous studies (Braithwaite et al., 1998; Craig et al., 2000; Gallimore et al., 1998; Gallimore et al., 2000, Jennings et al., 1998; Merryman and Cacioppo, 1997; Patterson, 1995; Patterson et al., 1997; Smith et al., 1997), however, it is clear from the results section that subjects in this study did not exhibit the OKCR.

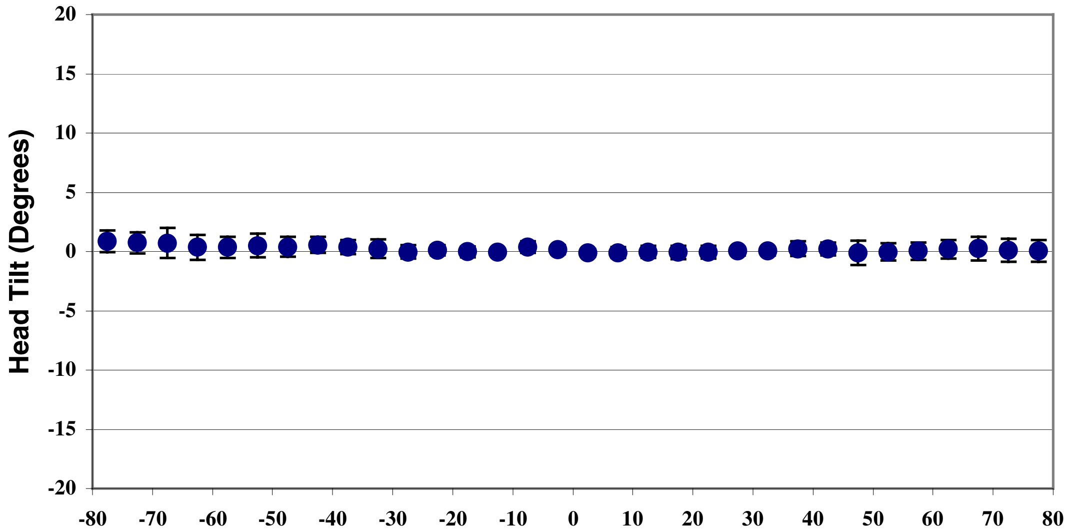

Figure 5. IMC Task – Average Head Tilt (Error bars represent standard deviation).

VMC Task Discussion

The most likely reason why subjects did not tilt their heads during this task was because of the nature of the task. In the previous studies, the VMC task consisted of pilots flying ground-oriented tasks: low-level flight, looking outside for waypoints, flying along rivers, etc. Pilots were not told specific bank angles to maintain; they were flying under less controlled and more realistic conditions. Hasbrook and Rasmussen (1973) observed the head-horizon tilt phenomena when pilots performed figure eights around pylons or S-turns over a road – both ground-oriented tasks. Head tilt, thus far, has been found to be present when pilots are actively viewing the real world and attending to its features. Pilots tilted their head to keep the horizon stationary in their visual field to maintain their orientation.

In the current study, subjects were flying at a high altitude (12,000 feet MSL) and were instructed via verbal command to bank their aircraft to a certain degree and maintain that angle of bank until they were told to level out. They were also instructed to maintain a commanded airspeed and altitude. To perform these tasks, pilots had to *attend to their instruments, not the horizon*; therefore the task strictly became an instrument-oriented task, not a ground-oriented one.

To complete the VMC task, the key portion of MIL-STD HUD symbology used was the bank scale (see Figure 3). This instrument functions such that the scale stays fixed and the pointer moves as the aircraft banks. Pilots determine their degree of bank, by reading the pointer position against the scale marking. In terms of figure-ground relationships, it is natural for pilots to keep the ground (the bank scale) fixed so they can accurately read the position of the figure (the pointer) against the ground (Goldstein, 1996). Therefore, keeping the scale fixed meant keeping the head upright – head movement might cause pilots to misread their bank angle.

In trying to maintain the commanded airspeed and altitude, an upright head position facilitated the accurate reading of the clock representations of airspeed and altitude, and the digital readout, which appeared in the center of the clocks. Tilting their heads could have caused an increase in time to recognize the airspeed and altitude information. This is confirmed by Friedman and Hall (1996), who found a linear relationship between time to recognize a stimulus and the distance of the stimulus from an upright position.

To summarize, pilots used bank, airspeed, and altitude information to perform this task. The symbology was designed to be interpreted when pilots are looking straight ahead with their head upright. Any head movement might cause one to not see symbology or to see it improperly. Therefore, pilots in the current study may have been actively keeping their heads in line with the symbology to allow them to interpret its information more efficiently – correct interpretation of the symbology facilitates spatial orientation. *The premise that pilots align their head with the cue that allows them maximum orientation information is a valid one in light of these results and what is known about the OKCR.*

IMC Task Discussion

Although it was hypothesized that the horizon *symbol* on the HMD might cause head tilt, this was not supported in the data. Because the IMC task was the same as the VMC task, subjects were focusing on the HMD symbology set to perform their task. The subjects may have been again focusing on the bank scale, not the horizon symbol. Central foveal vision is only 2° and although the horizon symbol was in their parafoveal view, subjects did not need to attend to that symbol to maintain orientation. They knew from their bank scale what their roll angle was. A quick crosscheck of the pitch scale gave them pitch information. Pilots were using the symbology to maintain orientation; therefore, they kept their head aligned with their primary orientation information.

General Discussion

There has been extensive research conducted on attention and HUD tasking, and limited research with respect to attention and HMDs. For example, Wickens and colleagues (Martin-Emerson and Wickens, 1997; Ververs and Wickens, 1998; Wickens and Long, 1995; Yeh, Wickens, and Seagull, 1999) showed that some tasks do not allow for the near domain (symbology) and the far domain (real world) to act synergistically. Similarly, McCann, Foyle, and Johnston (1993) supported two interesting theories pertaining to attentional demands and HUDs. First, parallel processing of non-conformal information on the HUD and information from the outside world is difficult for pilots to accomplish. Second, and more specific to the current research, a shift in attention was necessary to transition from the HUD information to the outside-world visual information. Only true divided attention tasks, (i.e., tracking a commanded path using instruments while looking for targets in the real world scene) support the knowledge of both domains. The task performed in the current study was definitely a focused attention task. Pilots could complete the task by focusing only on the symbology.

Conclusions

Knowledge of the interaction between attention and frame of reference may help reduce spatial disorientation incidents in two ways. First, when transitions between frames of reference are not necessary, channeling pilots' attention to specific information may eliminate casual or unintentional transitions, which may cause disorientation. Second, when transitions between frames of reference are necessary, facilitating the transitions via appropriate symbology designs will make the transitions as smooth as possible.

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Control of Posture, Subjective Vertical, and Body Scheme in Changing Gravitoinertial Field

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Summary

Spatial disorientation associated to decrease of sensorimotor performance may result in observers evolving in changing gravitoinertial field as created in aircrafts and other high dynamics modern vehicles. We have investigated the influence of body support orientation on the perception of egocentric and exocentric reference frames in 8 observers standing 80 cm off-center on a platform rotating at 120 deg.s^{-1}. Standing support was either a fixed horizontal board or a swinging pendulum. The perceptive task consisted in adjusting the orientation of a visual rod to indicate geocentric (subjective vertical (SV) and horizontal (SH)) and egocentric (head, trunk and platform orientations) references. Subjects' head and trunk, as well as rod orientations, were recorded with electromagnetic sensors (Polhemus Fastrack). The platform was equipped with sensors providing heel and toe vertical and lateral forces from both feet. Platform motion (when allowed to rotated in the swinging pendulum condition) was recorded with a potentiometer. We analyzed body postural reactions and compared veridical and perceived orientations in the two body support conditions.
In the horizontal platform condition, to compensate the mechanical constraints caused by the centrifugal force, subjects leaned toward the axis of rotation adopting a hyperbolic body shape. Head was aligned with the gravitoinertial force. SH was not sensed as orthogonal to the SV. Foot pressure (vertical and lateral components) was higher under the outer than under the inner foot. In the swinging pendulum condition, SV and body were aligned with the gravitoinertial vector. SH and SV were orthogonal. Foot pressure was the same under both feet. In both conditions, head and body orientations were overestimated. The data suggest that, as the gravitoinertial vector evolves, the vestibular system induces compensatory postural adjustments. The hyperbolic body shape is thought to be due to body multisegmental coordination. Other postural adjustments, thought to be neither of vestibular nor of visual origin, occur to keep the projection of the combined forces in the body support area. Although observers provided erroneous cognitive answers, they maintained postural balance in both conditions suggesting sensorimotor control to be independent of posture related cognitive processes.

Introduction

Mechanisms which govern the control of posture are still misunderstood. The human erect posture serves two main functions (Massion, 1994): on the one hand, posture counteracts the action of gravity by maintaining the body center of mass projection inside the supporting surface. On the other hand, posture constitutes an egocentric reference for perception and action, which partly depends on gravity, seen as a geocentric reference.

Human activities evolve under the influence of the gravitational field. Self generated movements as well as movements which human beings are submitted to (acceleration in vehicles, bends…) mainly product inertial and Coriolis forces. Inertial forces combine with gravity and generate gravitoinertial changes. To maintain balance during gravitoinertial changes, the axis linking the body center of pressure with the body center of mass must be kept aligned with the gravitoinertial vector. The gravitoinertial vector becomes then the new geocentric reference which must be used to maintain posture, instead of gravity.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

Several sensory information contribute to the control of posture (visual, proprioceptive, tactile, and vestibular information). But spatial disorientation generally occurs when subjects are deprived of visual references. Without any visual information, the control of posture mainly relies on a vestibular-somesthetic interaction (Mergner & Rosemeier, 1998). This vestibular-somesthetic interaction also participate to awareness perception of space and body orientation. The gravitoinertial vector direction and the support orientation constitute two major parameters of the environment constraints for postural control in darkness. Indeed gravitoinertial vector direction and body support orientation directly act on sensory inputs by modifying the ground reaction forces direction. It follows that, in this context, posture as well as perception would be modified.

The purpose of the present study was to determine the role of the support orientation in posture and perception when the gravitoinertial field is modified. We used a rotating platform to modify the gravitoinertial field. Two kinds of support were use: a fixed horizontal support (presenting discongruent sensory information during rotation) and a free pendulum support which tilted with the gravitoinertial vector (GIV) so that the support orientation was always approximately perpendicular to the GIV during rotation (sensory information were congruent).

Methods

Subjects

Eight healthy male subjects without vestibular or balance problem took part in the experiment (mean age : 24.12 ± 1.6 years old, mean weight : 71.62 ± 4.40 kg, mean height: 178.73 ± 2.44 cm). They gave informed consent to participate to this study.

Procedure and task

The experiment took place in darkness. Subject were standing head-front on a rotating platform, 80 cm from its vertical rotation axis (Fig. 1). A luminous rod was placed at eye level in front of the observer. Rod orientation could be adjusted by means of a joystick held manually. The behavioral task was to maintain postural equilibrium during platform rotation. The cognitive task consisted in adjusting the luminous rod to successively provide readings of 1- subjective vertical, 2- perceived body orientation, 3- perceived head orientation, 4- subjective horizontal and 5-perceived platform orientation.

The cognitive task was performed before, during, and after rotation on either a horizontal support, fixed with respect to the rotating shaft (Fixed condition) or on a pendulum support free to oscillate about a sagittal axis (Free condition), placed 30 cm above the subject's center of mass.

Subjects performed the tasks first when the platform was still motionless then when the platform was set into motion. During the acceleration phase which lasted 90 s and carried the platform at $120°.s^{-1}$ (GIV was then tilted by 19.7°), subjects were only asked to maintain their equilibrium. During the constant velocity phase which lasted 240s, subjects were asked to perform the cognitive task, starting 60s after the platform reached constant velocity (that is after semicircular canals returned to their resting state). Subjects' task was again to maintain equilibrium during the 90s deceleration phase. A final cognitive task was then executed 60s after the platform was stopped. Subjects were submitted to 4 rotation sequences for each support condition.

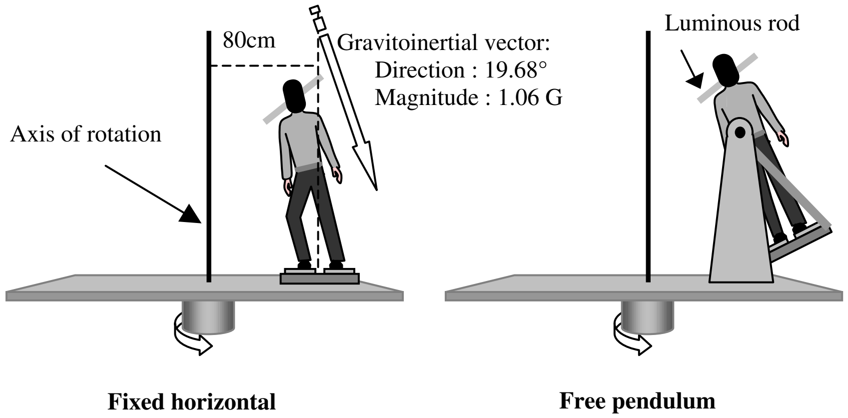

Fig. 1: Back view of a subject standing off-center on the rotating platform in the two experimental support conditions during rotation at constant velocity. Left drawing illustrates the fixed horizontal support condition and right drawing illustrates the free pendulum support condition.

Behavioral recordings

A strain gauge posturograph was used to monitor vertical and lateral forces applied under the subject's front and back of each foot. Head, trunk, and rod orientations were monitored by means of an electromagnetic movement device (Polhemus Fastrack). A potentiometer measured the free-pendulum support orientation in space.

Data analysis

Mean vertical and lateral forces as well as statokinesigrams were used to describe postural strategy and stability. The gravitoinertial vector applied at head level was calculated and used as the current geocentric reference. Head, body, platform veridical orientations were compared to subjective values provided by corresponding rod orientations. An Analysis of Variance assessed the significance of the differences between the experimental conditions. A post hoc test (Newman-Keuls) showed the specific differences. Null hypothesis were rejected when probabilities were below the threshold of 0.01.

Results

All subjects were able to execute postural and cognitive tasks in both support conditions, although they reported more difficulties to maintain postural equilibrium in the free-pendulum than in the fixed-support condition. The data corroborate subjects' reports. Comparison of postural and perceptual data collected before and immediately after rotation showed no significant differences ($p>.05$) thus demonstrating no after-effect. Consequently, these results will not be further commented.

Postural stability and force repartition

Fig. 2 illustrates vertical and lateral forces repartition between the two feet in the two support conditions during rotation. Results showed that during the rotation, subjects used a postural strategy specific to the support. In the Fixed condition, subjects tilted their body inwards by bending the inner leg and keeping straight the outer, to compensate for the centrifugal force. Vertical forces were significantly greater under the outer foot (73.04% ± 1.5 of the whole body weight, versus 26.96% ± 1.53 under the inner foot ($p<.01$)). The lateral forces were also significantly greater under the external foot (26.3% ± 0.46) than under the internal foot (8.35% ± 0.34) ($p<.01$).

In the Free condition, subjects kept the two legs straight. Vertical forces under the feet were still significantly different (Mean force under the inner foot: 55.03% ± 12.56; the outer foot: 44.97% ± 12.55; $p<.01$). Lateral forces were low under each foot but significantly greater under the inner foot (3.85% ± 0.73) than under the outer foot (1.04% ± 0.45) ($p<.01$).

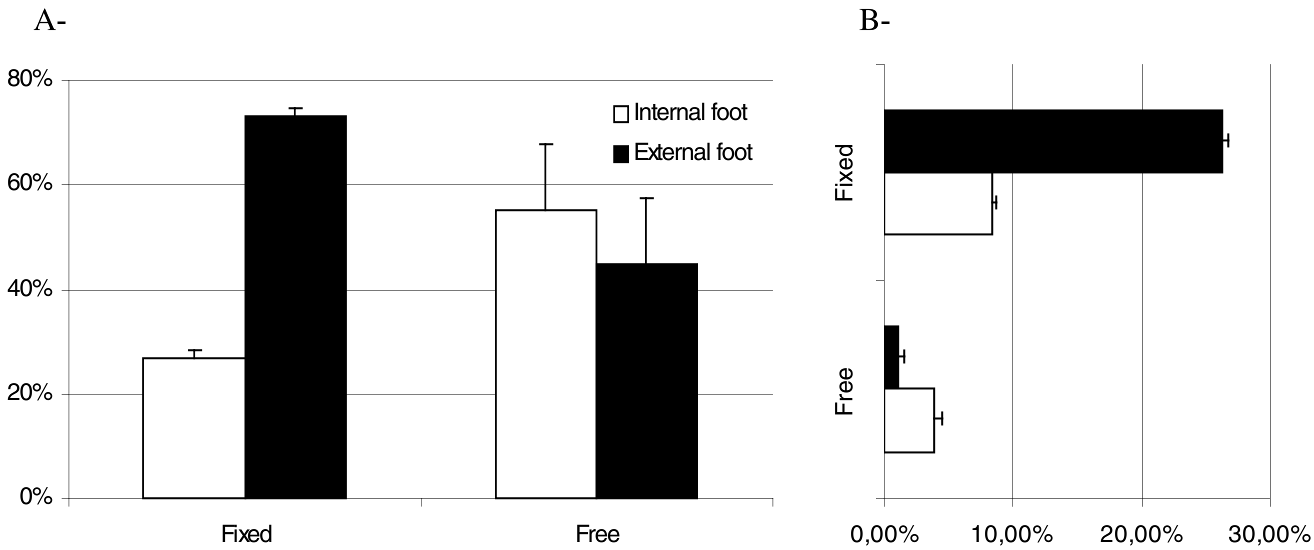

Fig. 2: Mean vertical (A) and lateral (B) forces which applied under each foot in the two support conditions during rotation. Whereas vertical forces are expressed in percentage of body weight, lateral forces are expressed in Newton.

Veridical orientation versus perceived orientation

During rotation in the Fixed condition, subjects' head tilted by 5.59° ± 0.88 inwards and was significantly different from head position before rotation (p<.01) and body tilted by 7.66° ± 4.3 inwards. The GIV acting at subjects' head level tilted by 13.43° ± 0.96 inwards. This vector was taken as the new geocentric reference to determine veridical vertical and horizontal during rotation.

Subjects perceived their head as tilted by 10.93° ± 9.15 inwards. Moreover, they perceived their body as being tilted by 14.9° ± 5.55 inwards. Vertical was perceived as tilted by 7.56° ± 4.5 inwards and horizontal as tilted by 4.7° ± 2.73 inwards. Subjects perceived the platform as tilted by 4.14° ± 9.15 inwards.

The post-hoc test revealed that the GIV and the subjective vertical differed significantly (p<.01). Moreover, subjective horizontal significantly differed from the axis perpendicular to the GIV (p<.01). Subjective vertical and subjective horizontal were not perpendicular in this support condition (p<.01). In addition, subjects significantly overestimated their head and body tilts (p<.01). However, there was no significant difference between the real and perceived platform orientations (p>.05).

During rotation in the Free condition, subjects' head and body tilted by 19.21° ± 1.84 inwards and 23.26° ± 4.7 inwards, respectively. The GIV tilted by 17.56° ± 0.91 inwards and the platform tilted by 26.7° ± 1.18 inwards.

Subjects perceived their head and their body as tilted by 23.28° ± 4.4 inwards and by 24.13° ± 2.9 inwards, respectively. They perceived the vertical and the horizontal as tilted by 16.1° ± 5.32 and by 15.17° ± 7.82 inwards, respectively and the platform as tilted by 23.22° ± 8.21 inwards.

The ANOVA revealed that there was no significant difference between veridical and perceived values in the Free condition ($F(1,29)=0.24287$; p>.05).

Comparison of the 'perception error' (defined as the difference between veridical and perceived values, Fig. 3) in the two support conditions showed that error in estimating the geocentric reference (vertical and horizontal) was significantly lower in the Free condition (p<.01). In the Free condition, vertical and horizontal were perceived as being orthogonal (p>.05). Subject correctly estimated their body orientation (p>.05). However the head tilt was still overestimated (p<.01).

To summarize, during rotation in the Fixed condition, subjects underestimated the tilt of the geocentric references (gravitoinertial vertical and horizontal). In addition, they overestimated their head and body tilts. The estimation of the platform orientation was not significantly different from its actual orientation.

In the Free condition, subject correctly estimated the orientation of the geocentric references as well as platform and the body orientation. but subjects still overestimated their head tilt.

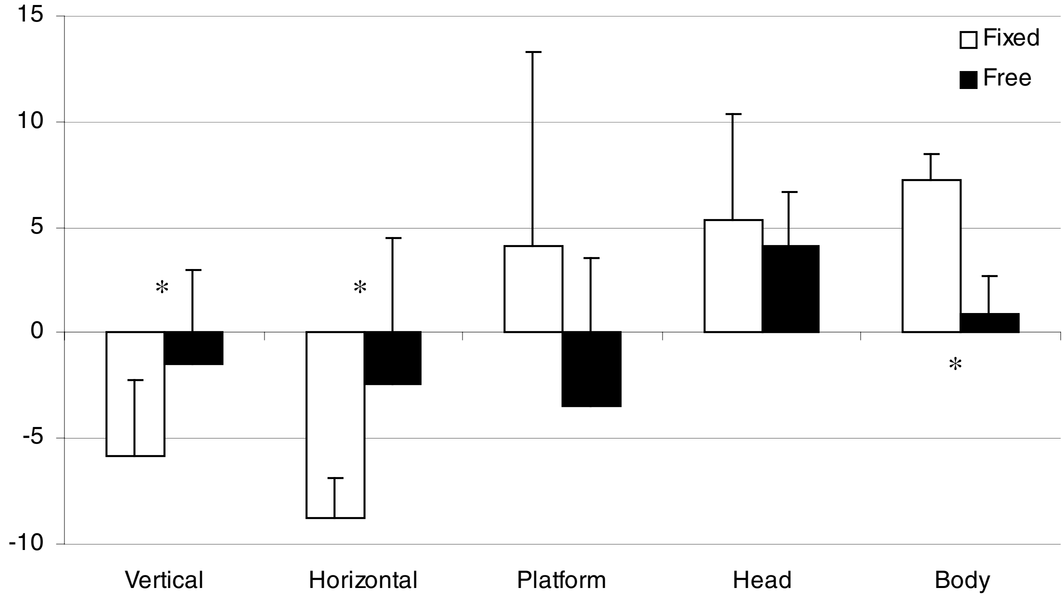

Fig. 3: Mean values of 'perception errors' (difference between veridical and perceived reference values) for the geocentric and egocentric references in the two support conditions during rotation.

Discussion

The purpose of this study was to determine cognitive and postural responses of subjects submitted to changes in gravitoinertial forces while standing on a fixed or on a free oscillating support without any environmental visual reference. In spite of the difficulty of the task, all subjects maintained their equilibrium and performed the perceptive task during rotation.

Rotation induced no after-effect on posture and perception. Before and after rotation, subjects perceived the different references with accuracy. This result differed from what Kaufmann et al. found in 2001. Indeed, they showed that subjects, after being exposed to gravitoinertial changes during 90 minutes, reported that they felt tilted in the direction opposite to the GIV after rotation. Moreover, there was an increase in the displacement frequencies of the center of pressure. The long period of rotation as well as the higher magnitude of the GIV (1.4G) used in their experiment might explain the presence of such an after-effect.

Concerning the postural responses, subjects used two postural strategies specific to support condition. During rotation on the fixed horizontal support, subjects' inner leg was bent as outer stretched. The body curved inwards (still remaining in a sagittal plane) to ensure the antigravity function. The postural forces (vertical and lateral) were mainly applied by the outer leg. On the free pendulum support, subjects kept their two legs straight and the forces were more balanced between the two feet. Some subjects reported to have applied more force under the inner foot in order to immobilize the free pendulum against its mechanical stop. This could explain the increase in the standard deviations we observed in the latter condition.

Concerning the perceptive responses on the fixed horizontal support, geocentric references were underestimated, in particular the subjective horizontal. Subjects overestimated their body tilt as well as their head tilt. The estimation of platform orientation showed great variability. However, when subjects were standing on the free pendulum support, they perceived geocentric values as well as body orientation with more accuracy. Riccio et al. (1992) found similar results for the perception of vertical by dissociating the orientation of the gravitoinertial forces from the orientation of the ground reaction forces, with the RATS (Roll-Axis Tracking simulator). Indeed, they found that the orientation of the subjective vertical depended on both gravitoinertial force direction and ground reaction forces direction needed to control balance. Our results allow us not only to extend the influence of the force orientation to the geocentric references (subjective vertical and horizontal), but also to show that ground reaction forces seem to influence more the subjective horizontal than the subjective vertical. Our results suggest that the visual subjective horizontal is not likely to be inferred from the visual subjective vertical but would depend more on the interaction between body and support. On this point of view, the congruence between sensory information become a major component to perceive the geocentric references as orthogonal. Thus, support orientation played an important role in the perception of spatial orientation. It influences the perception of geocentric references as well as perception of body orientation. However in our experiment, perception of head orientation was not influenced by the support orientation. According to Mergner & Rosemeier (1998), head orientation in space would be directly estimated from the GIV direction, whereas body orientation in space would be rebuilt from support orientation in space and body orientation on support. Several authors showed that the perception of egocentric references were less accurate than the perception of geocentric references (e.g. Darling & Hondzinski, 1999).

To conclude, we showed were able to achieve a fairly difficult postural task such as maintaining standing equilibrium in a changing gravitoinertial field, in spite of inaccurate geocentric and egocentric perceptions. Our results strengthen the idea that motor and cognitive representations are processed via parallel pathways. However, subjects interpreted the GIV as the gravity. This phenomenon was strengthened on the free pendulum support. Providing a support orthogonal to the gravitoinertial vector first favors well-balanced reaction forces repartition, second improves the accuracy to perceive the egocentric reference and gravitoinertial forces orientation to the detriment of the Earth-geocentric reference perception.

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Motion Sickness When Driving With a Head-Slaved Camera System

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SUMMARY

In a field experiment, we examined motion sickness incidence when driving with a head-slaved camera system. More specifically, we looked at the contribution to motion sickness of visual feedback on head roll and of stereoscopic view with the head-slaved camera system. The system was capable of motion in all three rotational degrees-of-freedom (DOFs). In the experiment, twelve subjects drove a car around a closed circuit in four different viewing conditions. In two conditions, no feedback on head roll was present by disabling the roll DOF of the camera platform (i.e., resulting in a 2 DOF system), and either mono view or stereo view was used. In the other two conditions, visual feedback on head roll was present (i.e., a 3 DOF system), and again either mono view or stereo view was used. As a baseline, subjects also drove with direct view, either with an unrestricted field-of-view (FOV) or with FOV-restricting goggles. The 2 DOF conditions were tested on a separate day from the 3 DOF conditions, and a direct view condition always preceded a condition with the head-slaved camera system. Upon completion of the driving task in each condition, the subjects filled in the motion sickness questionnaire (MSQ). Simulator sickness questionnaire (SSQ) total scores were derived from the MSQ. Results showed a significant difference between the 2 DOF and 3 DOF conditions (average SSQ total scores of 17.7 and 8.4, respectively). No significant differences between mono and stereo conditions were observed. These results indicate that motion sickness incidence with our head-slaved camera system can be reduced considerably by adding a roll component to the system.

INTRODUCTION

When driving with the hatch closed, drivers of armoured vehicles use periscopes to view the outside world. However, the field-of-view (FOV) of these periscopes is often very restricted, resulting in large blind areas in front and to the side of the vehicle and gaps between adjacent periscope views (Van Erp, Padmos & Tenkink, 1994). These problems impose restrictions on fast and accurate driving in many operational environments (Van Erp & Padmos, 1997; Van Erp, Van den Dobbelsteen & Padmos, 1998). As an alternative, we developed a head-slaved camera system for driving in such poor visibility conditions. This system consisted of a two degrees-of-freedom (DOF; heading and pitch) motion platform with two small cameras mounted on it, a mechanical headtracker, and a helmet-mounted display (HMD) for image presentation (see Figure 1). The camera motion platform is slaved to head movements of the driver, so that the camera orientation always matches the orientation of the driver's head. In this way, the driver can look around with the camera system in a natural manner. Also, other sensors, such as image intensifiers or thermal imagers, may be used to enhance the visibility of the driving scene in case of darkness, fog, snow, smoke or dust (e.g., Casey, 1999). Oving and Van Erp (2001a, 2001b) tested the feasibility of the head-slaved camera system for driving an armoured vehicle in a real world experiment. Their results showed that driving with such a head–slaved camera system is feasible, and that driving performance was even improved compared to the conventional periscope system. However, several drivers reported symptoms of motion sickness when driving with the system.

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Figure 1. The TNO Human Factors head-slaved camera system mounted on an armoured vehicle. On the left, the camera motion platform with the two cameras, the HMD and the mechanical headtracker is shown, while a close-up of the camera platform is shown on the right. The periscopes are located just in front of the hatch opening.

In general, motion sickness occurs when the brain receives inadequate or conflicting sensory information about the orientation and movement of the body in its environment (Reason & Brand, 1975). Especially information about the orientation of the head relative to the gravitational force is critical (Bles, Bos, De Graaf, Groen & Wertheim, 1998). The different sensory systems provide a coherent set of information about the orientation in the world in normal circumstances. However, discrepancies between the visual information and the vestibular and proprioceptive information about real world motions may occur when an indirect viewing system is used. Such discrepancies are known to provoke motion sickness.

At least four sources for such discrepancies exist in the TNO head-slaved camera system. First, of the six possible DOFs of head motion, only two rotations (i.e. heading and pitch) are measured and relayed to the camera motion platform. No visual feedback about the third type of rotation (i.e., head roll: the rotation around the line-of-sight) is presented in the HMD. However, drivers do roll their head during driving, even up to 20º or further (Zikovitz & Harris, 1999; Van Erp & Oving, in press). This omission of roll is believed to be more detrimental than the exclusion of the translations. When the eyes are focussed on an object, the effects of translational motions are more apparent in the periphery than in the central portion of the visual image. This is less so with head roll. When the head is rolled to one side, and the eyes remain stationary relative to the head, the complete retinal image is rotated in the opposite direction with the same magnitude. In addition, the HMD oculars fill up a large portion of the visual field of the eyes, up to a total of 130º per eye, while only the central 45º is used for displaying the camera images. Because of this lack of peripheral information, the drivers thus have to rely mainly on this central visual imagery in the HMD to determine head motions. However, the information on head roll that is normally available in this view, is now absent, and this may have led to the high incidence of motion sickness observed with the head-slaved system. Second, it is possible that the lower quality of the images, such as the relatively low resolution and contrasts, and presence of image smear, contributed to the motion sickness. This also relates to the use of stereo images in the system. For instance, Ehrlich (1997) reported a higher simulator sickness incidence with stereo images in a simulator, compared to mono images. So it is possible that (improper) stereo cues contributed to the motion sickness reports. In this view, it should be noted that we used a relatively large horizontal distance between the cameras (e.g., approximately 12 cm). This was done to create images with hyperstereo, which provides a stronger depth contrast and may result in a better binocular depth perception with camera view. Third, inherent delays in the head-slaved system result in discrepancies between the visually perceived orientation from the camera images and the vestibularly and proprioceptively sensed orientation. These delays are due to the video processing and the (dynamic) response characteristics of the motion platform. Fourth, the offset between the camera viewpoint and the physical position of the driver can also result in a discrepancy. For instance, in the field experiment, the camera platform was placed on the midline of the vehicle, while the driver was sitting on the left side (Oving & Van Erp, 2001a, 2001b).

We hypothesised that the omission of visual feedback about head roll may be the main contributor to the observed motion sickness with the system, because this omission results in the largest possible discrepancy between the visually observed motion and the vestibularly and proprioceptively sensed motion. This hypothesis is supported by a study of Craig, Jennings and Swail (2000), who used a head-slaved camera system for helicopter flying. They observed motion sickness symptoms when head roll compensation was absent in the camera platform (i.e., a 2 DOF system), but less so when it was present. We tested this hypothesis in the present study, by examining the effect of head roll compensation on motion sickness incidence with the TNO head-slaved camera system. In addition, we studied the effect of stereo view on motion sickness. Previous research has shown that the application of stereo images may prove beneficial for driving performance with a head-slaved camera system (Van Erp & Van Winsum, 1999). However, this advantage has to be weighed against any potential negative effects of using stereo view, such as the potential for motion sickness, because the choice for stereo view with a head-slaved viewing system has considerable impact on system specifications.

METHOD

Subjects

Twelve subjects, nine men and three women, voluntarily participated in the study. They were all employees of TNO Human Factors. Their age ranged from 22 to 36, with an average of 31 years. None of the subjects reported any uncorrected vision deficits.

Tasks

The study was performed on a closed circuit that is part of the Vlasakkers training ground of the Royal Netherlands Army. The experimental task of the subjects was to drive around a triangle shaped section of the circuit, with a length of approximately 250 m. In each condition, the subjects drove around the circuit freely for approximately ten minutes before they started with the experimental task, to accommodate them to the specific viewing condition. They subsequently drove eight laps around the triangle. The driving direction was changed from clockwise to counterclockwise, or vice versa, after each two consecutive laps.

Because it has been observed that head roll amplitude correlates positively with lateral acceleration (Van Erp & Oving, in press), the subjects were asked to drive the triangle at, more or less, comparable speeds in all conditions. In this way, potential differences in head roll amplitude between conditions are less likely the result of a difference in driving speed between conditions.

Apparatus

The system used by Oving and Van Erp (2001a, 2001b) on armoured vehicles was modified to enable head-slaved roll motion of the camera platform, in addition to the other two rotations (see Figure 2). Each DOF of the camera platform could be turned on or off individually. A common passenger car was then outfitted with a customised roof rack on which the modified camera motion platform of the head-slaved system was mounted. The camera platform was located on the left side of the car, above the driver's position, and approximately 60 cm above and 40 cm behind this position (see Figure 2). The mechanical headtracker was installed inside the vehicle, and rigidly attached to the driver's seat.

Figure 2. The modified head-slaved camera system (3 rotational DOFs) mounted on a passenger car (left side), and a close-up of the system (right side).

Two CCD cameras were mounted parallel on the platform with an inter-camera distance of 8 cm. This was smaller than the distance of 12 cm used by Oving and Van Erp (2001a, 2001b), although this horizontal separation is still considerably larger than the average inter-pupillary distance (i.e., 6.4 cm). The NTSC camera images were converted to VGA before they were displayed in the HMD. The HMD was a Kaiser ProView60, with a FOV of 48° (H) × 36º (V) and a resolution of 640 (H) × 480 (V) pixels. In combination with the lens type that was used, this resulted in a magnification factor of approximately 0.96 (i.e., objects in the camera images thus appeared to be slightly smaller than they were in reality). The update rate of the image system was 60 Hz. The delay in the image channel was approximately 50 ms, on average. This is exclusive of any dynamic latency due to the response characteristics of the motion platform. The mechanical headtracker allowed for 6 DOFs of head motion, but only registered the three rotations. The motion box of the mechanical headtracker did not limit normal head motions during driving.

Experimental design

Conditions

We looked at the effects of visual feedback on head roll, and of stereo view with the head-slaved camera system, on the incidence of motion sickness symptoms when driving with the system. The presence of head roll feedback was manipulated by either disabling the roll DOF of the camera motion platform, or by enabling this DOF. The two other DOFs of the system (i.e., heading and pitch) were always enabled, so the subjects drove with either a 2 DOF system or a 3 DOF system. When the roll DOF was disabled, the camera platform was always positioned such that it was horizontal (i.e., a roll angle of 0º) relative to the car. In the stereo view mode, both cameras were operational. In the mono view mode, the left side camera was turned off and the image of the right side camera was send to both displays of the HMD, so that both eyes viewed the same image (i.e., a bi-ocular display system). The combination of these two manipulations resulted in four experimental conditions with the head-slaved camera system: 1) 2 DOF with mono view, 2) 2 DOF with stereo view, 3) 3 DOF with mono view, and 4) 3 DOF with stereo view.

In addition, the subjects drove in two direct view conditions. In one condition, the subjects drove with view restricting goggles that limited their instantaneous FOV to 45º (H) × 35º (V). This FOV approximated the instantaneous FOV with the head-slaved system. In the other condition, no view restrictions were imposed (i.e., normal driving). These two conditions can be seen as baseline conditions for motion sickness incidence during driving.

Design

Each subject performed the driving task in all experimental conditions (i.e., a within-subject design). Each subject drove on two separate days, with the 2 DOF conditions always on a separate day from the 3 DOF conditions. This was done to avoid possible transfer of motion sickness symptoms between these two conditions. Due to scheduling restrictions, this was not possible for the mono and stereo view conditions. Each day consisted of four conditions: the two conditions with direct view (one with the FOV-restricting goggles and one without) and the two conditions (mono view or stereo view) in either the 2 DOF or the 3 DOF set-up of the camera platform. The subjects always started in a direct view condition, and then drove in one of the conditions with the head-slaved system. They subsequently drove in the second direct view condition and finished the day in the remaining condition with the head-slaved system. Thus a direct view condition always preceded a condition with the head-slaved camera system. Under the assumption that the direct view conditions would not be very provocative for motion sickness, this was done to reduce any potential transfer effects between the HMD-system conditions on a single day. Each condition lasted approximately 20 minutes, including the 10 minutes of free driving in the beginning of each condition, .

Six of the subjects started in the 2 DOF conditions, with three subjects starting with mono view and three subjects starting with stereo view. This also applied to the six subjects that started in the 3 DOF conditions. On the second day, the order of the conditions with respect to mono or stereo view was reversed for each subject. This also applied to the two direct view conditions: subjects that started in the FOV-restricted condition on the first day, started in the no-restriction condition on the second day, and vice versa.

Upon completion of the experimental task in each condition, the subjects were asked, among others, to fill in a modified version of the motion sickness questionnaire (MSQ). This modified MSQ included a 4-point scale for several questions, making it possible to derive simulator sickness questionnaire (SSQ) scores from it (Kennedy, Lane, Berbaum & Lilienthal, 1993). We used the SSQ total score, because our head-slaved camera system has more in common with a simulator than with the real world (e.g., degraded quality of the visual information, delays in the presentation of the visual images, etc.).

Statistical analysis

The SSQ total scores collected in the conditions with the head-slaved camera system were analysed with a repeated measures analysis of variance (ANOVA) with two independent variables: Roll feedback (present or absent) and View condition (mono view or stereo view). Regarding the first independent variable, roll feedback was present in the 3 DOF conditions, and it was absent in the 2 DOF conditions. The SSQ total scores for the direct view conditions were analysed separately, by means of an ANOVA with a single independent variable with 2 levels (unrestricted view or restricted view). In a subsequent analysis, the SSQ scores from the conditions with the head-slaved camera system and from the direct view conditions were analysed together. Data from non-significant effects in the previous analyses would be pooled for this comparison. Therefore, the specific statistical design for this ANOVA is presented in the Results section. When applicable, significant effects were analysed further with post-hoc Tukey tests. All analyses were performed with α set at .05.

RESULTS

The ANOVA on the SSQ scores in the head-slaved camera conditions showed a trend for a main effect of Roll feedback [$F(1,11)=4.60$, $p<.056$]. No main or interaction effects of View were observed, suggesting that the use of stereo images did not result in more, or less, motion sickness symptoms than the use of mono view. We therefore pooled the data regarding the viewing conditions in each DOF condition. The data in the direct view conditions were also pooled, because no significant difference was observed between the two types of baseline conditions (i.e., SSQ total scores of 2.5 and 3.2 for the unrestricted condition and the restricted-FOV condition, respectively).

The resulting pooled data were subsequently entered in a repeated measures ANOVA with Viewing system as a single independent variable with 3 levels (2 DOF, 3 DOF and direct view). The results showed a significant effect for Viewing system [$F(2,22)=8.56$, $p<.01$]. A post-hoc Tukey test indicated significant differences between the 2 DOF and 3 DOF conditions and between the 2 DOF and the direct view conditions ($p<.05$). The average SSQ total score was 17.7 in the 2 DOF condition, 8.4 in the 3 DOF condition, and 2.9 in the direct view condition. These results are shown in Figure 3. It also shows a qualitative description of the SSQ total score, based on simulator sickness research, as an indication for the severity of the reported sickness symptoms (Stanney, Kennedy & Drexler, 1997).

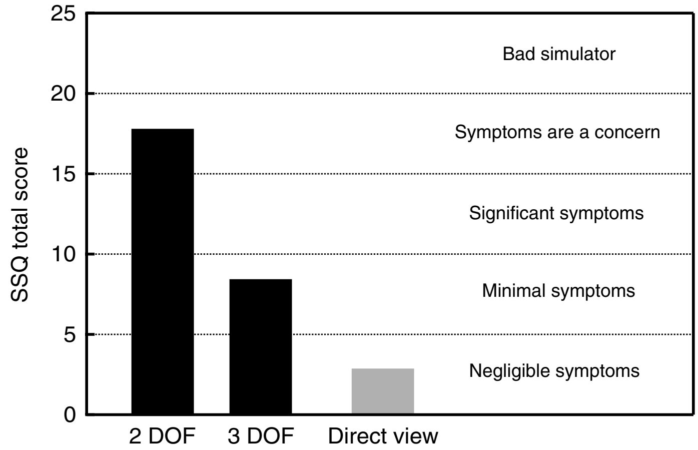

Figure 3. The average SSQ total score for the 2 DOF and 3 DOF conditions (black bars) and for direct view (grey bar). The verbal qualification of the SSQ total scores is taken from Stanney et al. (1997).

DISCUSSION

The results of the experiment clearly showed that visual feedback on head roll with the head-slaved system reduces motion sickness incidence. When visual feedback on head roll was present, substantially less motion sickness symptoms (as measured by the SSQ total score) were reported, than when such visual feedback was absent. This is in line with the results of Craig et al. (2000) regarding motion sickness reports with a head-slaved camera system for helicopter flying. Thus, enabling head-slaved roll motion of a camera platform is beneficial for the physical comfort of the operator.

However, there were still symptoms of motion sickness reported when feedback on head roll was present. This is reflected in the average SSQ total score in those conditions (i.e., a score of 8.4). This indicates that other characteristics of the head-slaved camera system, such as the inherent delays, also contributed to the observed motion sickness, but to a smaller extend than the absence of roll feedback. Therefore, research aimed at identifying these characteristics and their impact on motion sickness remains necessary. Please note that the absence of a statistical difference between the SSQ scores of the 3 DOF and direct view conditions should not be interpreted as indicating that there is *no* difference at all between these conditions. The power of the study may not have been high enough to detect significant differences between these conditions, since only twelve subjects were tested. Although it should also be noted that the power was large enough to detect differences between the 2 DOF and 3 DOF conditions.

The present experiment did not show an effect of stereo view on motion sickness, indicating that mono view and stereo view contributed equally to motion sickness. Again, this absence of a significant result does not necessarily mean that stereo view has *no* effect at all on motion sickness. Therefore, we can only conclude that stereo view certainly has less influence on motion sickness than the absence of head roll in the system.

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Almost Loss of Consciousness: a Factor in Spatial Disorientation?

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Summary

During high-performance flight, aircrew exposed to +Gz-stress may exhibit symptoms ranging from light loss (LL) to +Gz-induced Loss Of Consciousness (GLOC). If the stress is insufficient to cause GLOC, a syndrome called Almost Loss Of Consciousness (ALOC) can occur, which features deficits in motor and cognitive function. It is possible that these types of deficits may influence the nature or extent of spatial disorientation symptoms. In order to produce a definitive description of ALOC symptoms, nine subjects (one female) (Ss) were exposed to a series of repeated short +6, +8, and +10 Gz pulses at the NAVAIR Warminster centrifuge facility, which were lengthened in 0.25s increments until they experienced GLOC. Of a total of 161 +Gz pulses, 66 episodes of ALOC were identified. A math task before and during each pulse was used to determine short-term memory loss. Ss were required to press and hold a button spanning the time from initial LL symptoms to full recovery of vision. ECG and near infrared spectroscopy (NIRS) of relative cerebral tissue oxygenation (rSO2) were also recorded. Data analysis included a description of physical, cognitive, and emotional signs and the timing of their occurrence and resolution, and the timing of the LL from its onset to full recovery. The primary manifestation of ALOC symptoms was a disconnection between the desire to do something and the actual ability to act upon it. This could linger well beyond the end of the +Gz exposure. Physical symptoms included tingling, twitching, uncontrollable hand movements, hearing loss and transient paralysis. Cognitive deficits included confusion, amnesia, delayed recovery, a "vacant feeling" and difficulty in forming words. Surprise, concern and pleasant feelings were some of the emotional signs. There was a significant increase in the reduction in rSO2, greater overshoot in rSO2 (increase in oxygenation above baseline after the +Gz exposure), faster fall in rSO2 during +Gz-stress and prolonged recovery time associated with ALOC as compared to +Gz exposures without symptoms. Evaluation and comprehension of the range of events associated with these altered states of awareness can provide new insights into the relationship between the effects of +Gz-induced changes in the cerebrovasculature and the resultant changes in behavior on understanding the causes of spatial disorientation. With a more complete picture of the responses of both the vascular and vestibular systems, as well as the resultant behavior changes to environmental stresses, a more comprehensive approach to avoiding aircraft mishaps can be developed.

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Introduction

When aircrew of high-performance aircraft are exposed to +Gz-stress, a spectrum of symptoms can occur ranging from loss of peripheral vision ("light loss" - LL) to blackout to +Gz-induced loss of consciousness (GLOC). If the stress is insufficient to cause GLOC, deficits in motor and cognitive function can occur. This syndrome has been called Almost Loss Of Consciousness (ALOC). While ALOC has been noted in centrifuge studies since the early 1980's, and a recent survey (6) reported that a significant number of aircrew experienced emotional or cognitive symptoms in flight, a definitive description of the motor and cognitive deficits associated with ALOC does not exist.

Gillingham (3) defined the term *spatial disorientation* (SD) as "the condition wherein one not only has an orientational illusion but also needs to have correct perception of orientation for controlling his position, attitude, or motion." An *orientational illusion* is a "false percept of position, altitude, or motion, relative to the plane of the earth's surface." Orientational illusions occur whenever there is a misperception of displacement, velocity, or acceleration. These illusions have been categorized in accordance to their main cause - visual misperceptions and vestibular errors.

Spatial Disorientation has been categorized into Type I: Unrecognized SD, when the pilot is oblivious to the problem (e.g., channelized attention and task saturation); Type II: Recognized SD, when the pilot knows "something is wrong," but may not know the cause of the problem (e.g., a conflict between vision and semicircular canal stimulation); and Type III: Vestibulo-Ocular Disorganization or Incapacitation, when the pilot knows there is a problem but cannot orient him/herself and control the vehicle (2,3,4,7). In various studies conducted between 1954 and 1972, the percent incidence of fatal aircraft mishaps where SD either contributed to or was deemed the causal factor ranged from 4.8% to 26%. In a 1980 USAF study, it was found to be 18.4%. Finally, it has been reported that of the 15 Navy aircraft lost to noncombatant action in Desert Storm, 7 were SD mishaps (3,4,8).

Disorientation in flight has been called a psychological problem in that "it is concerned with human experience…" and therefore should be discussed in terms of psychology (1). However, the stimuli leading to it are physiologic and the event may be misclassified into other types of altered states of awareness (and vice versa) thus, it is appropriate to refer to the problem as psychophysiologic. It appears that some of the cognitive and emotional ALOC symptoms are similar to those experienced during SD. When investigating SD, it is important to consider if these ALOC symptoms contribute to the development and/or reactions of aircrew to SD.

Methods

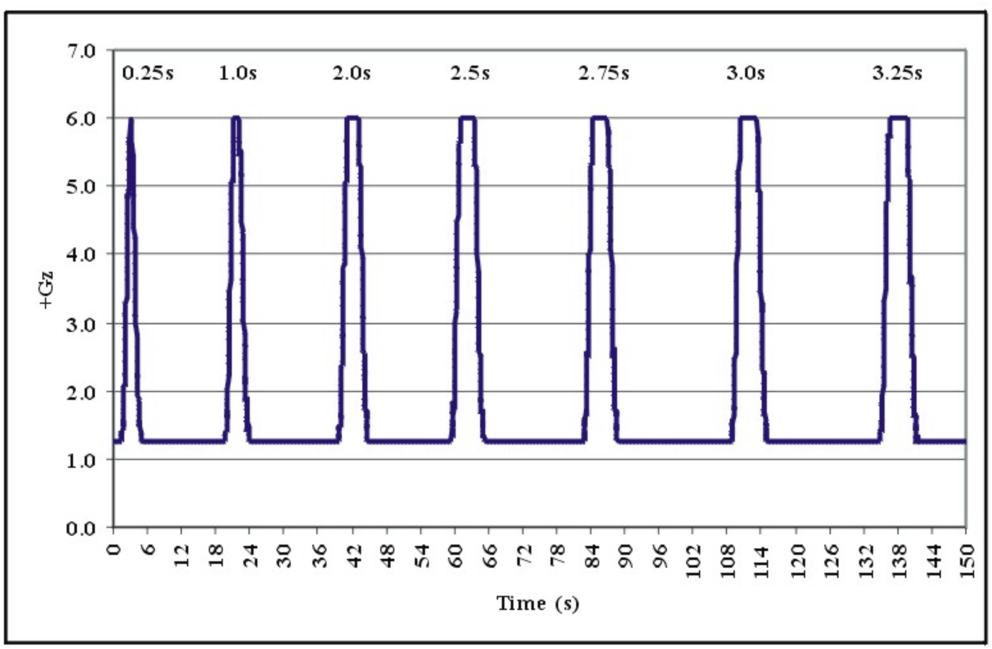
Nine (eight male) relaxed unprotected NAVAIR volunteers participated in this study. Subject characteristics are listed in Table I. All subjects indicated that they had no previous G-LOC experiences prior to this experiment. Subjects were exposed to a +6, +8, and +10 Gz pulse held for 0.25 second, then 1 second, then increasing in 1 second increments until LL reached 60° or 50% gray, at which point the increase was 0.5 second. Finally, when subjects reported total blackout, the increase was 0.25 second. There was a rest of at least one minute between each pulse. Figure 1 shows a typical pulse series. Onset time was 1.25 seconds to plateau, with an offset of 1.75 seconds to a rest plateau of +1.25 Gz. All nine subjects did not complete all six insertions. Physiologic monitoring included two channels of electrocardiography and relative cerebral tissue oxygenation was assessed using Near Infrared Spectroscopy (NIRS) probes on the forehead (5).

Subjects indicated their start of LL by pressing a button on an aircraft control stick in the centrifuge gondola. They were required to press and hold that button spanning the time from initial LL symptoms to full recovery of vision. Prior to and during each +Gz exposure until the onset of LL, subjects were asked to perform a math task (verbally reporting a running sum of a string of positive or negative numbers which were recited by the Flight Director over the communications system) that was used to evaluate if there was short-term memory loss after the +Gz exposure. This was determined after the run was completed and their vision was restored, by asking the subjects to state the last number they remembered.

Table I. The +Gz pulse length (seconds) in which ALOC symptoms were detected for each subject. A blank means that the subject had no pulse exposure at that +Gz level. Subject S3 repeated the +8 Gz pulse series (three days apart) without reaching GLOC each time. Subject S5 ended his first +6 Gz pulse series due to stomach discomfort, but completed a repetition six days later.

Subject	Gender	Age (yr.)	Height (in.)	Weight (lb.)	+6 Gz pulse length (s)	+8 Gz pulse length (s)	+10 Gz pulse length (s)
S1	M	26	70	130	2.5, 2.75	1.75, 2.0, 2.25	
S2	M	32	70	171	3.25, 3.5, 3.75, 4.0, 4.25, 4.5	2.0, 2.25, 2.75	
S3	M	38	70.5	215		1.0 (1st insert), 2.0, 2.5 2.0 (2nd insert), 2.5, 3.0	
S4	M	30	66	160	4.0, 4.5, 5.0, 5.5, 6.0	3.0, 3.25, 3.5, 3.75	2.5, 2.75
S5	M	26	69	145	4.0 (1st insert), 4.5, 4.75, 5.0 (2nd insert), 6.0, 6.5		
S6	M	25	72	175	5.0, 5.25, 5.5	1.5, 2.0, 2.25, 2.5	2.5, 2.75, 3.0
S7	M	44	67	170	4.0, 4.5, 5.0	2.5, 3.0, 3.5	
S8	M	29	70	225		3.0, 3.25	2.0
S9	F	34	64	135	5.0, 6.0, 6.5, 7.0	3.0, 3.5, 4.0	2.0, 2.5, 3.0

Figure 1. +6 Gz pulse series. The width of each succeeding pulse was dependent upon the light loss reported by the subject. Note that the rest interval between pulses has been shortened in this figure for clarity.



Every +Gz exposure was videotaped, and the video record included +Gz level, time of day, time at +Gz, heart rate (bpm), an indication of when the LL button was depressed and released, and analog traces of the +Gz and ECG signals.

Each +Gz pulse run was examined for the presence of ALOC signs and symptoms. Video records of ALOC candidate runs were digitized and individual runs (including pre-run, the +Gz pulse, offset and the entire recovery period) ported into a PC computer via a FireWire IEEE 1394 link for video/audio analysis using MGI VideoWave 4 SE software. The following parameters were collected:

1. A transcript of the conversation between the subject and Flight Deck personnel;
2. Identification of potential ALOC episodes at each +Gz pulse level and duration;
3. LL timing from its onset to full recovery, including the +Gz level at onset and the time during the post-run rest period that LL persisted;
4. A description and frequency of occurrence of motor and other physical symptoms;
5. A description and frequency of occurrence of indications of cognitive deficits, altered states of awareness, and emotional signs and symptoms;
6. Subject performance in the math task.

NIRS analysis provides an indication of the relative change in cerebral tissue oxygenation, or rSO2 (5). rSO2 is a dimensionless quantity. Due to technical difficulties, not all NIRS data sets were suitable for analysis. Six sets were available at +6 Gz, and five each for the +8 and +10 Gz series. NIRS data analyses computed the following values and timing parameters:

1. A 60 second average preceding the onset of each pulse was calculated and served as the baseline (rSO2base). Subsequent baselines were calculated for each pulse in a given series and compared to determine if rSO2 returned to the same level throughout the centrifuge insertion (ΔrSO2base).
2. The time from +Gz onset to the minimum rSO2 (Tmin) and the difference between the baseline and minimum rSO2 (rSO2min);
3. The time from minimum rSO2 to the maximum overshoot (Tmax) and the difference between the minimum and maximum rSO2 (rSO2max);
4. The total time (Ttotal) from +Gz onset until rSO2 returned to a value of zero after the run (rSO2zero);
5. The rate of change (slope) from +Gz onset to rSO2min (Δmin);
6. The rate of change (slope) from rSO2min to rSO2max (Δmax);
7. The rate of change (slope) from rSO2max to rSO2zero (Δzero);
8. The time from rSO2min to rSO2zero (Tmin2zero);
9. The time from rSO2max to rSO2zero (Tmax2zero).

Statistical analyses included general linear model analysis of variance with a Fisher's least squares difference post hoc test to determine the source of any detected differences. Subjects were treated as random variables and fixed variables included +Gz level and symptom type (GLOC, ALOC, or normal). Additional tests were run on the NIRS data in which the order of the symptom type was a factor. This used GLOC, the previous three ALOC incidents preceding the GLOC (A1 was the pulse immediately preceding GLOC, A2 preceded A1, A3 preceded A2), and next two +Gz pulses without symptoms prior to the ALOCs ("normal", N1 before A3 and N2 before N1) as fixed factors. Statistical significance was set at the alpha < 0.05 level.

Results

During the +Gz pulses (a total of 161), 66 instances were identified in which ALOC symptoms occurred. At +6 Gz, there were 29 episodes from seven subjects, at +8 Gz, there were 28 episodes from eight subjects, and nine episodes from four subjects occurred at +10 Gz. Table I lists the pulse durations at each +Gz level where ALOC was identified for each subject.

Table II contains a summary of the persistence of LL and the +Gz pulse length when ALOC or GLOC occurred. Total LL includes the time during and after the +Gz exposure in which the LL button was depressed. LL often continued after the centrifuge returned to the rest plateau. There was no statistical difference in the total LL time or the persistence of LL into the rest period as the +Gz level increased.

Table II. Duration (mean ± standard deviation) and range of reported light loss (seconds) and +Gz pulse duration (seconds) during 66 ALOC and 20 GLOC episodes.

	+Gz level	Duration	Range
Total Light Loss Period	6	8.9 ± 3.5	3.1 to 14.9
	8	7.9 ± 4.8	1.2 to 20.4
	10	11.0 ± 4.4	4.9 to 16.6
Persistence of Light Loss after completion of the +Gz pulse (i.e. during rest plateau)	6	4.7 ± 3.5	0.0 to 11.3
	8	5.2 ± 4.2	0.5 to 15.9
	10	8.1 ± 5.0	0.7 to 14.1
Length of +Gz pulse during ALOC	6	4.8 ± 1.1	2.5 to 7.0
	8	2.5 ± 0.7	1.0 to 4.0
	10	2.6 ± 0.4	2.0 to 3.0
Length of +Gz pulse during GLOC	6	5.7 ± 1.6	2.75 to 7.5
	8	3.3 ± 0.6	2.5 to 4.25
	10	2.9 ± 0.4	2.5 to 3.25

The mean length of a +Gz pulse associated with ALOC was significantly longer during +6 Gz than +8 or +10 Gz, based on a one factor ANOVA ($F = 48.0$, $p < 0.001$). Results of an ANOVA comparing the pulse length during ALOC and GLOC episodes indicated that the pulse length associated with GLOC was significantly longer at +8 Gz ($F = 6.5$, $p < 0.015$), but not at +6 Gz ($p = 0.078$) or +10 Gz ($p = 0.124$).

The most consistently reoccurring physical, cognitive, and emotional symptoms are summarized in Table III, along with the number of incidents, the number of subjects reporting those experiences, and the number of subjects who experienced those symptoms during more than one pulse exposure.

Table III. Summary of the most prevalent physical, cognitive and emotional responses during ALOC, including the total number of episodes, number of subjects demonstrating symptoms, and number of subjects expressing these symptoms more than once.

Category	Symptom	No. Episodes	No. Subjects	Repetitions
Physical	Tingling in the hands, arms, and face	40	7	6
	Dazed or blank facial expression	27	8	6
	Twitching in arms and hands	20	8	5
	Eye movements	18	5	3
	Whole body shaking	16	4	2
	Facial relaxation	10	5	2
	Overall loss of control	10	5	3
	Hearing loss	8	4	2
	Transient paralysis	6	4	2
Cognitive deficits	Confusion	34	9	9
	Amnesia	22	7	6
	Delayed recovery	18	7	5
	Difficulty in forming words	8	3	2
	Disorientation	7	6	1
Emotional	Pleasant feeling	13	7	4
	Concern	7	6	1
	Surprise	5	3	2
	Unpleasant feeling	4	2	2

Listed in Table III there are various signs and symptoms associated with delayed cognitive ability. These include an inability to remember or a delay in regaining full faculties after the end of the +Gz exposure. The general category “amnesia” included the inability to recall: (a) the offset of the +Gz pulse; (b) when the subjects released the LL button; (c) what to do; and (d) events during the pulse. Subjects either reported being generally confused or they stated specific symptoms related to confusion, such as: (a) “I don’t know how I got here / where I am?”; (b) “I know where I am but not why I’m here”; (c) “I don’t know what’s happening”; (d) “I don’t know why I’m twitching”; (e) “I don’t know why the GLOC beeper is on”; and (f) “I don’t know what to do”. Loss of memory occurred during 37% of all ALOC episodes.

The most common emotional signs and symptoms described by the subjects included pleasant, unpleasant, concerning and surprising feelings. Under the category of “pleasant” feelings, subjects described their sensations as energized, enthralled, giddy, or pleasurable. When subjects reported being concerned, it was related to their inability to move or speak or when they expressed apprehension that they were getting close to GLOC. Reactions described as surprise were related to either not experiencing GLOC when they thought that they had, or to hearing the GLOC beeper when they thought they did not GLOC.

Table IV lists symptoms under the category of “altered states of awareness (ASA).” This includes the subjects’ perceptions of unusual sensations and whether or not they felt that they had experienced ALOC or GLOC. ASA includes a vacant feeling (19% of all ALOCs), aptly described by subjects as a “numbness of the brain” and a “frozen moment in time.” Subjects indicated that they experienced a sort of a void in that they knew where they were but could do nothing, physically or mentally, during that period. Another sign was a floating sensation (Table III) and/or a feeling of being suspended in the ejection seat (32% of all ALOCs). While these symptoms only appeared in four subjects, they were very consistent in three of them and occurred at more than one +Gz level. Table IV also includes some subjects’ perceptions of whether or not they experienced ALOC or GLOC.

Table IV. Symptoms of “altered states of awareness” during ALOC episodes at given +Gz levels, including the total number of incidents, the number of subjects experiencing a given symptom, and the number of subjects experiencing the symptom multiple times.

Symptom	No. Episodes	No. Subjects	Repetitions
Thought that they experienced ALOC	9	3	2
Thought that they experienced GLOC	5	3	1
Not sure if they experienced GLOC	5	4	1
Knew that they had not experienced GLOC	5	2	2
Floating Sensation	15	4	3
Fuzzy Headed	5	3	1
Light Feeling or Suspended Sensation	5	3	2
Lightheaded	3	3	0
Mumbles or Speaks During LL	5	3	1
Vacant Feeling (“Numbness of the Brain” or a “Frozen Moment in Time”)	12	5	3

Tables V-VII summarize the events and responses relative to the math task. There were 35 correct and 31 incorrect responses during the math task. For the latter, the last number recalled was often prior to the pulse, and seven subjects recalled a number that was not in the sequence (during eight pulses). Table V summarizes the mean pulse length in which subjects correctly and incorrectly recalled the last number in the math task at each +Gz level. While the incorrect responses tended to occur at longer +Gz pulse lengths, this was not always the case. For example, during his series of +6 Gz pulses, subject S4 had incorrect responses at 4.5 and 5 seconds and correct responses at 5.5 and 6 seconds. The difference in the pulse length between correct and incorrect responses was not statistically significant.

Table VI lists the point and mean time during the +Gz pulse when subjects spoke the last number in the sequence. Subjects said the last number during the first 2.0 ± 1.2 seconds of the plateau portion during 26 of 29 ALOC episodes at +6 Gz (three during G onset). Of these, 14 were said 1.3 ± 0.8 seconds before the onset of LL and 12 were stated 1.1 ± 0.7 seconds after LL onset. During the +8 Gz pulses, the last number was said twelve times during the first 0.6 ± 1.1 seconds at plateau, eleven times during 0.9 ± 0.5 seconds during G onset, and five times 0.7 ± 0.4 seconds before the pulse began. During the +10 Gz pulses, the last number was said five times during the first 0.9 ± 1.0 seconds at plateau, two times during G onset, once before the pulse began, and once during G offset.

Table V. +Gz pulse length (mean ± standard deviation in seconds) corresponding to correct and incorrect recall of the last number during the math task. A number without a standard deviation means that there was only one response at that pulse level. A '-' indicates that there was no corresponding response at that +Gz level. A blank means that the subject had no pulse exposure at that +Gz level.

Subject	+6 Gz		+8 Gz		+10 Gz	
	Correct	Incorrect	Correct	Incorrect	Correct	Incorrect
S1	2.50	2.75	1.75	2.13 ± 0.18		
S2	3.67 ± 0.38	4.08 ± 0.52	2.38 ± 0.53	2.50		
S3			1.88 ± 0.63	2.75 ± 0.35		
S4	5.17 ± 1.04	4.75 ± 0.35	3.50 ± 0.35	3.25 ± 0.35	2.38 ± 0.53	-
S5	4.00	5.35 ± 0.86				
S6	5.13 ± 0.18	5.50	2.00 ± 0.50	2.25	2.50	2.88 ± 0.18
S7	4.50 ± 0.71	4.50	-	3.00 ± 0.50		
S8			2.50 ± 0.50	3.25	2.00	-
S9	6.17 ± 1.04	6.00	3.25 ± 0.35	4.00	2.00	2.75 ± 0.35
Group Mean	4.45 ± 1.19	4.70 ± 1.08	2.46 ± 0.68	2.89 ± 0.62	2.22 ± 0.26	2.81 ± 0.09

Table VI. The point during the +Gz exposure when the last number was stated.

Symptom	Total No. Subjects	Total No. Incidents	Incidents at +6 Gz	Incidents at +8 Gz	Incidents at +10 Gz
Said last number before the pulse began	5	5	-	4	1
Said last number during the G onset	7	16	3	11	2
Said last number during the +Gz plateau	9	43	26	12	5
Said last number during the G offset	1	2	-	1	1

The inability to recall the last number spoken may be an indication of short-term amnesia. In about half of the ALOC cases, even though subjects continued to respond during the +Gz exposure, they forgot what they said after the run was completed – either only remembering a number prior to G-onset (sometimes several numbers in the sequence before the last number), stating a number not in the sequence, or remembering only one of two digits of the number. Table VII lists the point during the +Gz exposure when the incorrectly recalled last number occurred. It is interesting to note that in 14 of 20 cases, the number that the subjects thought was the last number said **during** the +Gz pulse was actually said **before** the pulse began. For the eight instances in which the number they recalled was not in the sequence, six responses were off by one digit. In five of six cases, it appeared that the number in the sequence that the subjects recalled was not one that they said, but was the number (or part thereof) voiced by the Flight Director. For example, the sequence might have contained 12 **+ 7** = 19, and the subject said that the last number was 1**7**.

When subjects recalled an incorrect number after a +6 Gz pulse, the last number the subjects stated occurred 1.5 ± 0.2 seconds before LL began (by two subjects during five pulses) and 1.2 ± 0.7 seconds after LL onset by five subjects (during nine pulses). If the last number was correctly recalled, it typically was said before the onset of LL, according to the results of a Kruskal-Wallis Multiple-Comparison z Test ($z=2.67$, $p=0.002$).

When subjects incorrectly recalled the last number in the math task, there were other indications of amnesia or delayed cognitive ability. For the +6 Gz pulses, incorrect responses coincided with forgetting the G offset (3 of 4 cases), inability to remember events during the pulse (2 of 3 cases), and not remembering when they released the LL button (2 of 2 cases). Six of ten symptoms relating to confusion coincided with incorrect recall and in three of four cases, subjects held onto the LL button too long. Also, there was a statistically significant relationship between incorrect recall and when the last number was said after the onset of LL. After the +8 Gz pulses, eight of thirteen indications of amnesia and 13 of 16 signs of confusion were noted along with incorrect recall. Five of the nine reports of slow recovery also corresponded to incorrect recall.

An example of the rSO2 response to a +6 Gz pulse is shown in Figure 2. ALOC symptoms occurred during this run. The rSO2 overshoot after the completion of the +Gz exposure was typical. Table VIII lists a summary of the mean NIRS timing parameters and also includes light loss and the timing of the last number spoken during the math task for comparison. The table indicates that rSO2min occurred after the end of the +Gz plateau, either during the +Gz offset or after the run was completed. The overshoot (rSO2max) occurred after the run is finished and complete vision had been restored. Vision is restored before rSO2max, particularly during the ALOC runs. Table IX contains the mean slope, rSO2min and rSO2max values.

Table VII. The point and frequency during the +Gz exposure when the incorrectly recalled number occurred and the number of responses that were not in the number sequence at all. Of the eight incidents listed in which the number recalled was not in the sequence, six were off by one digit (indicated in **bold** font).

Point at which incorrect number was recalled	Total No. Subjects	Total No. Incidents	Incidents at +6 Gz	Incidents at +8 Gz	Incidents at +10 Gz
Before the pulse began	8	14	3	8	3
During G onset	3	3	1	1	1
During the plateau	3	3	3	-	-
Number recalled not in sequence	7	8	4 (**3**)	4 (**3**)	-
Number not in sequence off by one digit	6	6	3	3	-

There were no differences between the rSO2 baseline computed before and after the various pulses. rSO2min was significantly smaller during +6 Gz pulses than +8 or +10 Gz pulses ($F = 6.6$, $p = 0.002$) and smaller during normal as compared to ALOC or GLOC runs ($F = 20.7$, $p < 0.001$). Tmin was significantly longer during +6 Gz pulses than +8 or +10 Gz pulses ($F = 6.8$, $p < 0.002$) and shorter during normal as compared to ALOC or GLOC runs ($F = 34.4$, $p < 0.001$). rSO2max was significantly smaller during +6 Gz pulses than +8 Gz pulses ($F = 4.6$, $p = 0.013$) and varied between the three symptom types, with normal the smallest, followed by ALOC, with GLOC with the largest ($F = 36.8$, $p < 0.001$). Tmax was shorter during +8 Gz compared to +6 and +10 Gz pulses ($F = 5.6$, $p < 0.005$). Ttotal was shorter during normal as compared to ALOC or GLOC runs ($F = 7.8$, $p < 0.001$). It took less time to reach rSO2min (Δmin) at +8 and +10 Gz than during +6 Gz pulses ($F = 15.0$, $p < 0.001$). The rate of change between rSO2min and rSO2max varied between the three symptom types, with normal the most gradual, followed by ALOC, with GLOC with the fastest Δmax ($F = 6.5$, $p = 0.002$). Tmin2zero was less during normal compared to ALOC runs ($F = 4.9$, $p < 0.010$) and Tmax2zero was less during normal compared to both ALOC and GLOC runs ($F = 6.9$, $p < 0.002$).

Table VIII. Mean NIRS timing parameters (seconds) relative to the +Gz onset. The mean length of the +Gz pulse, the time the subjects said the last number, the time from +Gz onset when light loss (LL) began and ended are also shown. EOP: time from +Gz onset to the end of the plateau; EOR time from +Gz onset to the End Of the Run.

Symptom	EOP	EOR	Last No.	LL onset	LL ends	Tmin	Tmax	Ttotal	Tmin2zero	Tmax2zero
+6 Gz pulse										
N2	4.35	6.10	1.89	3.56	9.14	5.66	20.42	38.74	33.07	18.32
N1	5.17	6.92	2.76	3.85	10.36	6.47	21.69	41.65	35.18	19.96
A3	6.00	7.75	3.58	3.85	13.20	7.16	19.60	40.72	33.55	21.12
A2	6.50	8.25	3.85	4.08	12.88	7.01	23.12	46.85	39.84	23.73
A1	6.88	8.63	4.25	3.62	13.86	7.42	19.95	47.47	40.04	27.52
GLOC	7.40	9.15	3.86	3.08	19.69	8.13	21.46	54.75	46.62	33.29
+8 Gz pulse										
N2	2.50	4.25	-0.19	2.87	4.95	4.93	27.10	41.05	36.11	13.94
N1	3.25	5.00	0.73	3.63	9.35	6.02	19.88	46.16	40.14	26.27
A3	3.85	5.60	1.25	3.03	11.68	5.94	25.55	52.04	46.09	26.49
A2	4.25	6.00	2.04	3.00	11.24	6.40	23.41	46.21	39.81	22.79
A1	4.60	6.35	1.30	3.05	11.49	6.64	20.38	48.13	41.49	27.74
GLOC	4.80	6.55	1.48	3.52	15.66	7.14	17.55	42.25	35.11	24.70
+10 Gz pulse										
N2	2.50	4.25	1.51	4.07	7.17	4.99	23.93	39.76	34.77	15.83
N1	3.10	4.85	1.15	3.59	8.92	4.51	22.06	52.70	48.19	30.64
A2	4.08	5.83	1.23	3.11	14.53	5.95	24.61	55.76	49.81	31.15
A1	4.19	5.94	1.79	2.64	14.01	5.96	21.31	51.02	45.06	29.72
GLOC	4.40	6.15	2.20	3.43	16.32	5.03	24.14	46.90	41.87	22.76

Figure 2. Example of NIRS response to 3.25 s +6 Gz pulse. rSO2min occurs at 6.8s, rSO2max at 14.8s, and rSO2zero at 35.2 s.

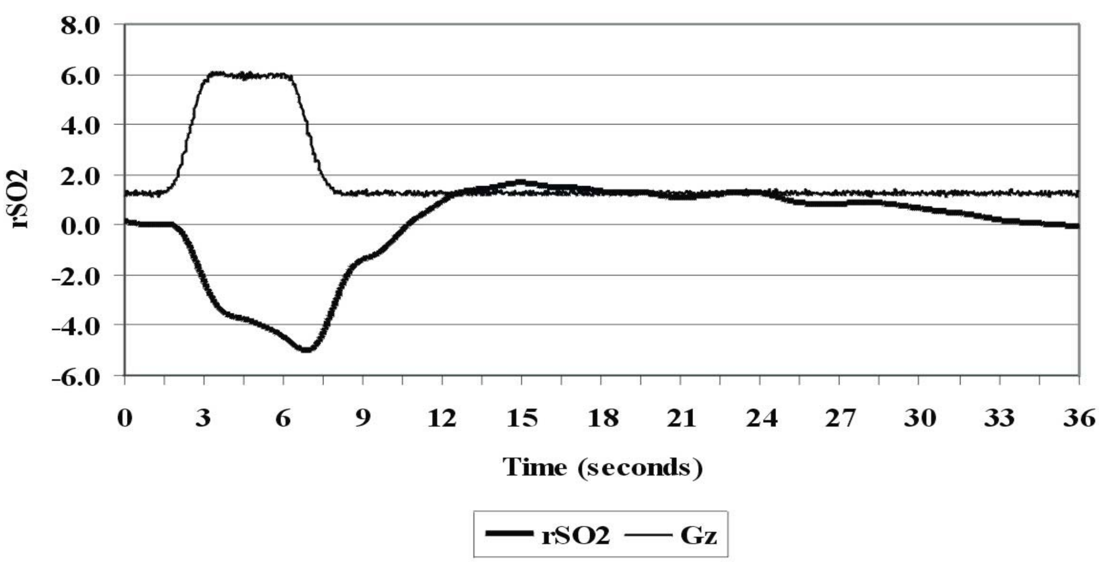


Table IX. Mean NIRS rSO2 values and slopes (change in rSO2 over time in seconds). The mean length of the +Gz pulse (seconds) is also shown. EOP: time from +Gz onset to the end of the plateau; EOR time from +Gz onset to the End Of the Run.

Symptom	EOP	EOR	rSO2min	rSO2max	ΔrSO2base	Δmin	Δmax	Δzero
+6 Gz pulse								
N2	4.35	6.10	-4.42	6.43	0.08	-0.80	0.68	-0.15
N1	5.17	6.92	-4.81	6.89	-0.04	-0.76	0.72	-0.13
A3	6.00	7.75	-4.89	6.99	0.10	-0.67	0.79	-0.11
A2	6.50	8.25	-4.37	6.76	-0.06	-0.61	0.64	-0.15
A1	6.88	8.63	-4.36	6.73	0.13	-0.59	0.71	-0.09
GLOC	7.40	9.15	-5.01	8.16	0.09	-0.57	0.67	-0.10
+8 Gz pulse								
N2	2.50	4.25	-5.17	6.99	0.12	-1.05	0.53	-0.20
N1	3.25	5.00	-5.08	7.12	0.09	-0.89	0.67	-0.12
A3	3.85	5.60	-5.84	7.73	-0.07	-0.98	0.52	-0.11
A2	4.25	6.00	-6.13	8.17	0.11	-0.99	0.70	-0.13
A1	4.60	6.35	-6.52	9.08	-0.10	-1.03	0.72	-0.15
GLOC	4.80	6.55	-6.92	9.73	0.09	-0.98	1.14	-0.14
+10 Gz pulse								
N2	2.50	4.25	-4.80	6.31	0.06	-1.17	0.47	-0.11
N1	3.10	4.85	-4.17	6.10	-0.09	-0.85	0.41	-0.06
A2	4.08	5.83	-6.01	7.91	0.11	-0.99	0.50	-0.07
A1	4.19	5.94	-5.16	8.39	0.04	-0.83	0.60	-0.11
GLOC	4.40	6.15	-5.45	8.65	0.07	-1.01	0.63	-0.16

In the results of the statistical analyses runs to determine the effects of order, there was an effect for Tmin. While N2 was significantly shorter than each of the ALOCs and GLOC, N1 was only less than A1 and GLOC ($F = 5.2$, $p < 0.001$). For Ttotal, while N2 was shorter than the other pulses, there were no differences between N1, the ALOCs or GLOC ($F = 2.7$, $p = 0.027$). As seen in the other ANOVA, rSO2min was less during N1 and N2 compared to GLOC, though not the ALOCs ($F = 2.5$, $p = 0.037$). For rSO2max, N2 was less than GLOC, A1 and A2, N1 was only less than GLOC and A1, and A3 was less than GLOC ($F = 8.3$, $p < 0.001$).

Discussion

Detecting the occurrence of ALOC by an external observer is difficult (Table III). There are a few physical manifestations that occurred in most of the subject pool. A dazed or blank expression and a relaxation of the facial muscles is a visual indication of ALOC (occurring in 59% of all ALOCs). Involuntary movements may be seen in the arms and hands (21% of all ALOCs). This myoclonus often continued after the centrifuge returned to the rest plateau. For example, the sensation of muscle twitching in the hand persisted as long as three minutes in S3. The use of the light loss button was a useful tool in this respect in that when subjects repeatedly pressed the button, in several cases it appeared to indicate a lack of voluntary control of their hands. Also, two subjects consistently noted that their whole bodies were shaking.

In order to detect the other physical symptoms listed in Table III, tingling in the hands and arms (33% of ALOCs), tingling in the head and lips (30% of all ALOCs), a sensation that subjects momentarily lost control (16% of all ALOCs), hearing loss (13% of all ALOCs), and transient paralysis (10% of all ALOCs), subjects would have to be specifically asked. As for the latter symptom, subjects indicated that while they wanted to move their arms, for example to turn off the GLOC beeper, it took a while before they could do so.

One clear cognitive symptom of ALOC was a delay in the subjects' ability to regain full function after the ALOC episode. Seven of nine of the subjects indicated that during at least one ALOC episode (14% of all ALOCs), they continued to depress the LL button even though they realized that their vision recovered. A majority of the subjects indicated that it took a long time to fully recover or it "took a while to realize what to do."

A dramatic cognitive deficit was the inability of some subjects to speak after the run was completed. They knew what they wanted to say but they could not form the words. This indicated the presence of a disconnection between cognition and ability to act upon it. Typically, the Flight Director did not talk to the subjects after the run until they released the LL button. When subjects were obviously having difficulty speaking (14% of all ALOCs), it persisted a few seconds after full vision returned. While this symptom occurred in a minority of the subjects, it is a clear indication of the operational significance of ALOC – nothing could be more hazardous than a situation in which a pilot cannot physically act on what his mind is directing him to do.

Subjects frequently expressed confusion during ALOC episodes. It was not unusual for subjects to express confusion at more than one pulse length for a given +Gz level and at more than one +Gz level. 25% of all ALOC events were associated with a generalized state of confusion. They often could not clearly articulate why they were confused or when they could, they indicated that they did not have a clear grasp of what was happening or why something was happening.

The NIRS results provide an indication of the relation between the behavioral symptoms and the underlying changes in cerebrovasculature. The greatest drop in head level oxygenation typically occurs during the +Gz offset or continues into the rest period. Symptoms continued to persist well into the period of oxygen recovery (the rSO2max) during the rest plateau, including light loss, confusion, tingling and involuntary movements. An important finding with implications for the SD community is the significant increase in the reduction in rSO2 (rSO2min), greater overshoot (rSO2max), faster change in rSO2 during +Gz-stress (Tmin2zero) and prolonged recovery time associated with altered states (ALOC) as compared to +Gz exposures without symptoms.

These findings clearly have safety of flight implications and stress the need for training aircrew about ALOC. If after exposure to +Gz stress, aircrew require extra time to regain complete awareness and if they do not recognize that they are experiencing ALOC symptoms, the risk to life and aircraft grows.

Overall, there were fewer emotional than physical or cognitive symptoms reported. Subjects expressed more positive than negative emotions. This may be due to the fact that they were in the centrifuge (as opposed to in-flight). Several subjects commented that they knew they were safe because they knew that they were being closely monitored. While some subjects did express a mounting anxiety during succeeding pulse runs as they anticipated reaching GLOC, it is difficult, if not impossible, to completely emulate the complete experience of flight, *e.g.* mounting adrenaline levels associated with operating in a dangerous environment. It is interesting to speculate whether there would be fewer positive responses during actual flight conditions. Pilots have reported a feeling of euphoria/happiness/relaxation immediately upon regaining consciousness in-flight. Thus it may be difficult to assess this type of question in that emotions and behavior may change once the victim of altered states of awareness (GLOC, ALOC, SD, etc) realizes their true situation.

Many of the symptoms observed in this experiment were also reported in a USN and USAF survey of 70 pilots (6). The authors noted the occurrence of sensory and motor abnormalities, amnesia, confusion, euphoria, and reduced auditory response. This lends credence to the assumption that this is not simply a centrifuge related phenomenon. However, one may speculate that the heightened levels of hormonal flow during aerial maneuvers associated with increased attention or perception of danger (fight or flight), it is possible that recognition and recovery from ALOC symptoms may be different in-flight than was documented in the centrifuge.

Spatial Disorientation is classified as pilot error. Accident investigation boards that identify mishap causes necessarily derive them from a chain of events. The finding of "pilot error" may then be an attractive solution whenever the data available does not identify equipment, engine, or other component failure as the cause of the accident. Moreover, the pilot is not around to "explain him/herself." Certain accidents and incidents may be due to altered states of awareness such as frank GLOC or ALOC but are misclassified as SD and other errors for lack of relevant data. It is important to recognize this problem. For example, GLOC is a syndrome replete with sequelae that may either be confused with or facilitate SD. The problem becomes more difficult when addressing ALOC in that it defies a solid definition or a distinguishable sequence of events. Ercoline et al (2) discuss the various terms that have been assigned to Spatial Disorientation since the 1930's including Pilot Vertigo, Loss of Situational Awareness (LSA), Mid Air Collision, and Controlled Flight into Terrain (CFIT). For example, pilots experiencing SD also suffer from LSA and CFIT could be a result of any of the three types of SD. Indeed, these events, CFIT, ALOC, SD, GLOC, LSA are all altered states of awareness.

Consider the following hypothetical scenario describing a class A mishap during a fly-by: The pilot comes in low and fast at 200 feet, he then rolls hard into a +5 Gz turn until the last few degrees when the nose starts to slice down into the ground. Should we define the cause of the accident to be SD? At which point in the sequence of events did SD occur? There is a path of information flow that "involves the processing of largely numerical data from flight instruments into derived orientation information by higher cerebral centers" (3). Could the pilot have been momentarily confused due to his exposure to +Gz and subsequently unable to integrate information and make appropriate decisions? Would the pilot, if he had survived, have remembered and/or recognized the event as SD? What if the pilot experienced ALOC, would he report it as such or as SD? These would be difficult questions for a surviving pilot to answer. Some stories reported by pilots as SD events follow: "On my FIRST solo away from the field, severe VFR/CAVU, I practiced steep turns and got a 'dizzy' feeling, I tried to recover from the turn, but instantly felt a marked increase in G-forces. I immediately realized I was messed up, and *put my head in the cockpit, and recovered on instruments*.... no further problems..." "Learning aerobatics over the ocean. Instructor took over after I got confused trying to do a cloverleaf." "... I was lucky, and it made me a much better, *conscious instrument pilot*." (9)

Conclusions

ALOC is an insidious problem that affects cognitive, motor and emotional responses of aircrew. The gaps in memory, delayed recovery time, and reduced control over voluntary muscles all increase in-flight danger. The difference in the duration of +Gz stress necessary to induce GLOC as compared to ALOC was only shown to be significant for the +8 Gz pulses. Most importantly, the effects linger well beyond the end of the +Gz plateau, into the subsequent rest period. Recovery of cerebral oxygen levels from rSO2min took an average of 33 to 50 seconds. In some individual cases, recovery to within 10% of baseline rSO2 did not occur before the next run was initiated. Recognition of these symptoms by pilots may decrease the potential for LSA or SD, thereby reducing the number of mishaps attributed to "pilot error."

Unfortunately, the finding of SD as the cause of a fatal mishap cannot always be based on actual data, i.e. the testimony of the mishap pilot. It seems prejudiced to assign pilot error as the cause of a mishap when at best there may only be voice recorder data. More research is required by the Crew Systems community to understand this complex syndrome to better define protection system control specifications and training methods.

It is therefore proposed that consideration of the types and kinetics of these symptoms, as well as the responses of the vestibular system, is important towards understanding the overall phenomenon of spatial disorientation.

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Tactile Torso Display as Countermeasure to Reduce Night Vision Goggles Induced Drift

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Summary
The degraded visual information when hovering with Night Vision Goggles may induce drift that is not noticed by the pilot. We tested the possibilities of counteracting these effects by using a tactile torso display. The display consisted of 64 vibro-tactile elements and presented information on the desired direction of motion only (simple version), or also included information on the current motion direction (complex version). The participants flew in a fixed-base helicopter simulator with either full vision or with simulated night vision goggles. The results showed performance improvement for both tactile display variants compared to hovering without a tactile display. This improvement was present in the NVG conditions (mean reduction of the position error of 22% in the horizontal direction and of 41% in the vertical direction), but also in the full vision condition (mean reductions of 32 and 63%, respectively). Also, performance with a tactile display is less affected by the introduction of a secondary (cognitive) task than performance without a tactile display. The complex variant of the tactile torso display tends to be less effective than the simple variant. We hypothesize that this effect may be due to what we call "*tactile clutter*".
This simulator study proves the potential of intuitive tactile torso displays in reducing drift during hover. The display is so effective that it even results in performance improvement in full vision conditions. Also, the results prove that tactile displays can be applied in fast man-in-the-loop tasks. Finally, advanced tactile displays that are able to present more complex stimuli open up new possibilities of information presentation, but may also introduce tactile clutter.

Introduction

Tactile torso displays consist of numerous vibrators attached to the torso in a matrix arrangement. They convey information by presenting localized vibrations to the torso. Since these stimuli are directly mapped to the body coordinates, tactile displays are able to present spatial information in an intuitive way (Gilliland & Schlegel, 1994; Wood, 1998; Schrope, 2001; Van Erp, 2001a; Van Veen & Van Erp, 2001). This 'tap-on-the-shoulder' principle goes for locations (left is left, and right is right), but also for motion (forward is forward, and backward is backward). The potential of tactile displays as a countermeasure for reducing Spatial Disorientation has already been shown (Raj, Suri, Braithwaite & Rupert, 1998). The initial applications were based on relative simple technologies, and were restricted to activating single locations. Recent developments in the field of tactile torso displays allow to present much more complex spatio-temporal patterns, including motion and ensembles of stimuli (Van Erp & Van Veen, 2001).
We employed an advanced tactile torso display to counteract one of the problems that arise when flying with Night Vision Goggles (NVGs). The reduced visual information in this situation (quantitatively as well as qualitatively) may result in degraded motion perception. As a result, a rotary wing aircraft may drift substantially without the pilot detecting motion or a changed position. The tactile torso display in the current study consisted of 64 elements and was able to stimulate single locations as well as (apparent) motion.

Paper presented at the RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures", held in La Coruña, Spain, 15-17 April 2002, and published in RTO-MP-086.

Objectives and hypotheses

The first objective of the present study is to investigate whether a tactile torso display can help to compensate for degraded visual information. We investigate the effects on performance and on mental effort. Therefore, we had a complicated design. First, we compared full vision and NVG vision. Our expectation was that the tactile display would improve the performance when flying with NVGs, but had no or only a small effect under full vision. Besides the day/night vision manipulation, we also manipulated the visual cues in the environment. Again, we expect a larger positive effect of the tactile displays with a sparse environment compared to a rich visual environment. Finally, we manipulated the (cognitive) workload by adding a secondary task (Continuous Memory Task). This was done to investigate the claim that tactile displays are 'intuitive', which implies low level information processing. We expected therefore, that the presence of a tactile display would make performance less affected by cognitive load.

Design of the tactile codes

At present, there is no such thing as a set of guidelines to develop tactile torso displays, partly because of the rapid but recent development of hardware and concepts. We will discuss some critical factors here. A real methodology must be developed before tactile displays can be systematically and consistently designed.

Besides the usual Human Factors issues (e.g., consistency and robustness), some specific issues are important for tactile displays. Van Erp and Van den Dobbelsteen (1998) give a more complete overview. For the present application, in which location and timing are the primary parameters, the following issues are important:

1 *Ecological meaning*. An ecological or intuitive display is a display that presents information in such a way that it is processed directly and sheer effortless. This is potentially a strong point of tactile torso displays. Recent research showed that spatial information is easily interpreted. Main reason is that the display is directly mapped onto the body coordinates. This holds for static points, but also for motion (forward is forward and backward is backward). The use of motion has not been extensively investigated yet. An optimal design employs these intuitive properties.

2. *The pace of presentation*. A tactile display will not be able to present large amounts of information in parallel like a visual display can. The resolution of tactile displays is too small, and the occurrence of spatio-temporal interaction may hamper perception (see also point 4). This means that messages have to be presented serially and that the required duration can be an obstructing factor (Van Erp, 2001b).

3. *Resolution*. Even with up to 100 elements, the resolution of the display is limited. This means that locations are 'rounded' to the nearest element. Especially when presenting patterns (e.g., lines), this may be important. A straight line on a low resolution display may not be straight at all. Also, aliasing effects can occur. Possible counter measures are the application of perceptual illusions (such as apparent position or the "tactile rabbit"; Geldard & Sherrick, 1972), or the preprogramming of specific spatial patterns (e.g., tilted lines). The latter means that the elements in the display will no longer be ordered along a regular matrix pattern.

4. *Interference*. The spatio-temporal integration of two or more signals may result in the occurrence of a completely new percept. This may happen with parallel as well as with sequential presentation. For instance, two signals presented in phase but to different locations will result in the percept of a single stimulus in-between (e.g., Sherrick, Cholewiak, & Collins, 1990), and two points separated in time and location may result in a motion percept from the first to the second points (Kirman, 1974; Sherrick, 1968).

5. *Presenting complex continuous signals*. The tactile channel may not be very good in processing complex continuous signals (i.e., using a tactile display as tracking display), at least compared to other sensory channels. There are indications that tracking error with a tactile display is up to four times the error with a visual display (e.g., Hahn, 1965; Triggs, Lewison, & Sanneman, 1974). Part of this difference may be caused by inherent differences between the employed displays (e.g., no preview with tactile displays). No recent results with more advanced tactile displays are available yet.

We designed two variants of the tactile display. The simple display variant presents information on the direction of the drift (error) only. The complex variant presents error information as well as additional information on the current direction of motion.

Simple version.
The simple version only presents information on the direction of the set point (i.e., the origin in 3D space). This is implemented by activating single points of the display. Two analogies can be used here. The first is that the activated element indicates the desired direction (as would be done with indicating the desired route or the next waypoint). The second analogy is that the element indicates the direction of the drift, i.e., liking bumping into a virtual wall. We chose the first coding principle, for of two reasons. The first is the resemblance with the waypoint analogy; a consistent coding in this case would be that the vibration indicates the desired direction. Second, this coding unambiguously indicates the optimal direction of motion, while the virtual wall analogy indicates the direction to avoid, which leaves the pilot with the choice to determine the optimal steering action (many motion directions will free the pilot from the wall, of which the 180 degrees opposite (mirrored through the body midline?) is the optimum). By using a belt around the torso, we integrated the two horizontal degrees of freedom into one direction in the horizontal plane. Van Erp (2001a) already showed that such an integration leads to a robust and accurate percept of direction. The desired motion in the vertical direction was indicated by activating elements under the thighs and on the shoulders (for set point below and above current altitude, respectively).

Complex version.
In version 2, the momentaneous motion direction is added to the direction of the set point. Motion was not presented by single points, but by a (apparent) motion across the torso. This was implemented in the horizontal plane by two points that move symmetrically towards the direction of motion (e.g., when moving forward, the points would start at the left and right side and move forward to meet right in front; when moving to the left, the points would start on the spine and on the navel and move simultaneously to the left. Combined with the coding of the desired direction, moving in the right direction means that the motion points end in the point that indicates the direction. As long as these points don't coincide, the pilot moves in the wrong direction.

Methods

Participants
Twelve participants flew in a rotary wing simulator. They were students of the Royal Dutch Airlines Flight Academy (KLS). Their mean age was 22.4 years, their mean flying experience was 160 hour (range 110 – 200 hours). They had no experience with tactile displays and the TNO flight simulator. They had no particular experience with helicopter hovering. They were paid the equivalent of Euro 50 for their participation.

Figure 1. Example of a simulator image in the 'rich' environment.

Task and simulator
The participant flew scenarios consisting of three phases: hovering, low level flight, and hovering again. This paper reports only on the two hovering phases. In these phases, the instruction was to hold a specific position in 3D space. The two hovering phases were at different locations in the database: one location was a visually rich environment (including unique objects and objects taller than the hovering altitude; see Figure 1), the other environment was sparse (only fields and woodland). Each phase consisted of an initial stage (30 s) and a recording stage (120 s without a secondary task, 120 s with a secondary task, see below). At the beginning of each hovering phase, the helicopter was at ground level. The instructed altitude was 15 m. During the initial stage, the altitude error was presented as a head-up display. Directly after the 30 s initial stage, the altitude error was switched off and the recording stage started. The altitude set point for the recording phase was the instructed altitude (15 m), the horizontal set point was the horizontal position at the onset of the recording phase.

The flight simulator consisted of a helicopter mock-up with full controls and a cylindrical dome measuring 140 by 40 degrees of visual angle. The helicopter model was a simplified, linearized helicopter model, fine-tuned by an experienced Couger pilot. Three Evans & Sutherland® Simfusion image generators generated the visuals. NVG vision was simulated by the image generators (in hardware). In the NVG conditions, the participant wore field size restricting goggles (field size 40 degrees, 100% overlap, no optics).

During the second half of each hovering phase, the participant performed a secondary task: the auditory continuous memory task (CMT). The CMT consists of series of spoken letters of the Dutch alphabet and was presented through headphones. Each time the subject detected a target letter a button had to be pressed, that was positioned on the stick near the thumb. There were four target letters (A, B, C and D). The letters had also to be counted in separate tallies. The button had to be pressed twice when a target letter was presented for the second time. If this response was correct, the subject heard the word "correct". When the subject pressed the button at an incorrect moment or when an omission was made, the word "wrong" was presented in the headphone. After the feedback ("correct" or "wrong") the tally for the last letter had to be set to zero. The letter's E, G, H, P, T, V and W were not used because the sound of these letters could be confused with the target letters. Target letters were never presented in succession. Thirty percent of the letters were targets. The duration of the CMT was two minutes (see Veltman & Gaillard (1996, 1998) for further details).

Tactile display

The tactile display was developed by TNO Human Factors. The display consisted of 64 elements. These were custom build and based on DC motors that were housed in a PVC contactor with a contact area of 1.5 by 2.0 cm. The elements vibrated with a frequency of 160 Hz. The elements were build-in in a stretch fleece vest. The elements were organized in 12 columns (exactly at 1, 2,...,12 'o clock), and five rows (equally distributed between the navel and the nipples). The four remaining elements were attached to both shoulders and under both thighs. The direction of the origin was indicated by pulsing elements. The pulsing rhythm was dependent on the error. For errors smaller than 1 m no signal was given, for errors between 1 and 5 m the rhythm was 100 ms on - 200 ms off, for errors larger than 5 m the rhythm was 50 ms on – 100 ms off. The motion direction signal consisted of five (discrete) steps in the direction of motion. The onset of the next element coincided with the offset of the former element with a pause between the last burst and the onset of a new series. Burst duration and pause were speed dependent 0 ms (speed lower than 0.1 m/s), 100 ms burst and 200 ms pause (speed between 0.1 and 1 m/s), and 50 ms and 100 ms pause (speed higher than 1 m/s).

Performance measures and data analyses

For each of the phases, we calculated the position error, separately for the horizontal direction and the vertical direction. Performance on the CMT was measured by the Reaction Time to the double clicks and the percentage correct. Finally, participants indicated their subjective workload after each run on the Rating Scale Mental Effort (Zijlstra & Van Doorn, 1985).

Each performance measure was analyzed by a repeated measures analysis of variance: Vision (full vision / NVG vision) × Tactile display (none / simple version / complex version) × Environment (rich / sparse) × CMT phase (before CMT / during CMT).

Procedure

The participants came for a full day. They came in pairs and took turns after each session. After arrival they were introduced to the general procedures of the experiment. During the morning they were trained on the task and the simulation environment. This training consisted of four 20-minutes sessions for each participant, with full and NVG vision and with and without CMT. During the afternoon, each participant flew three blocks of two runs. Each run took 13 minutes net flying time.

Results

Hover performance

We discuss the results per performance measure. The position error in the horizontal direction showed several main effects and two-way interactions, see Table 1. The main effects of Vision, Environment, and CMT showed that performance degrades with night vision, a sparse environment and during the CMT phase, respectively (the means can be deducted from Figures 2-4). The interactions between these independent variables showed that the effects strengthen each other. Of primary interest however, were the main effect and interactions with the tactile display. The main effect showed performance improvements with the tactile displays: The simple variant reduces the error with 27%, the complex variant with 25%, compared to the no-suit condition. The interactions are depicted in Figures 2-4. The non-significant interaction between Vision and Tactile suit (Figure 2) showed that both tactile suits reduced the position error considerably compared to the no-suit condition, not only in the night vision condition (mean reduction 22%), but also in the full vision condition (mean reduction 32%). The interaction between Environment and Tactile suit (Figure 3) showed that the error reduction of the tactile suits is larger in the sparse environment (28%) than in the rich environments (20%). Finally, the interaction between CMT and Tactile (Figure 4) showed that there is no effect of the tactile suits in the phase before the CMT task, and a large error reduction (35%) during the CMT phase.

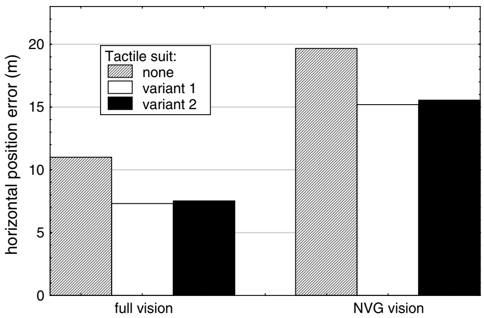

Figure 2. Horizontal error as function of visual and tactile display condition.

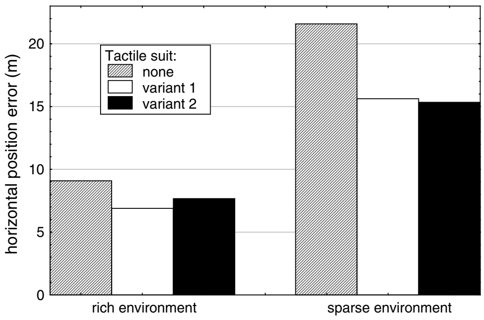

Figure 3. Significant interaction of environment and tactile display on the horizontal error.

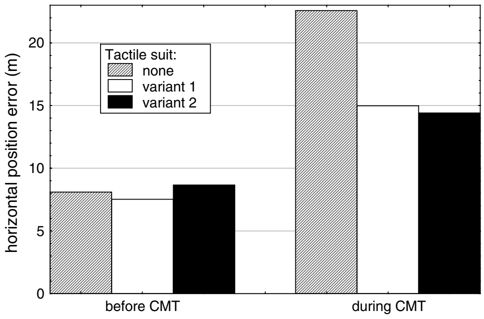

Figure 4. Significant interaction of the presence of the secondary task and tactile display on the horizontal error.

Table 1. ANOVA results on the horizontal position error (higher order effects omitted).

Effect	df	F-value	p-level
Vision (V)	1, 11	93.35	.001
Tactile (T)	2, 22	5.88	.009
Environment (E)	1, 11	59.28	.001
CMT (C)	1, 11	57.34	.001
V × T	2, 22	104.92	.95
V × E	1, 11	93.51	.005
T × E	2, 22	35.04	.025
V × C	1, 11	53.27	.001
T × C	2, 22	45.67	.001
E × C	1, 11	120.20	.001

An overview of the ANOVA results on the vertical error is presented in Table 2. The main effects of Environment and CMT showed degraded performance in the sparse environment compared to the rich environment (means 2.18 and 0.77 m), and during the phase with the CMT compared to without the CMT (means 1.78 and 1.17 m), respectively. The main effect of Tactile suit showed an error reduction of 55% for the simple variant and 47% for the complex variant, compared to performance without a tactile suit. The non-significant interaction of Vision and Tactile suit indicated an error reduction both with NVG vision and full vision (see Figure 5). The interaction of Tactile suit and CMT is depicted in Figure 6. This interaction showed that the error reduction of the tactile suits is larger in the CMT phase than in the phase before the CMT.

Table 2. ANOVA results on the vertical error (higher order effects omitted).

Effect	df	F-value	p-level
Vision (V)	1, 11	2.77	.12
Tactile (T)	2, 22	16.06	.001
Environment (E)	1, 11	17.45	.002
CMT (C)	1, 11	5.52	.039
V × T	2, 22	1.58	.23
V × E	1, 11	2.90	.12
T × E	2, 22	1.93	.17
V × C	1, 11	1.79	.21
T × C	2, 22	3.66	.043
E × C	1, 11	3.04	.11

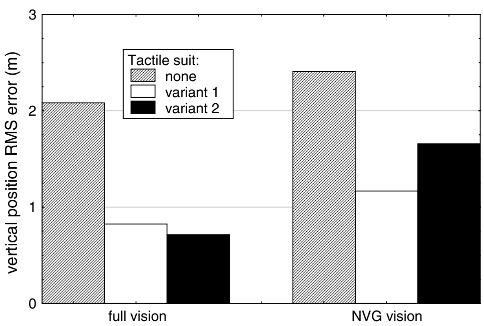

Figure 5. Vertical error as function of vision and tactile display.

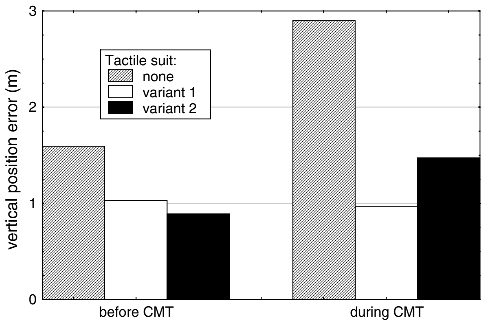

Figure 6. Significant interaction of the presence of the secondary task and tactile display on the vertical error.

Performance on the secondary (CMT) task
There were no effects on either the reaction time (mean 900 ms) or the percentage correct (mean 90%).

Mental effort rating
Two main effects on the mental effort rating were significant: Vision ($F(1, 11) = 7.18$, $p = .021$) and CMT ($F(1, 11) = 14.40$, $p = .003$). The means showed a higher mental effort with night vision compared to full vision (means 57.8 and 48.4, respectively) and higher mental effort in the CMT phase compared to the phase before the CMT (means 56.9 and 49.3, respectively).

Discussion

The first observation is that both tactile display variants improve the performance on the horizontal as well as the vertical dimension. Compared to the no-suit condition, the simple variant reduces the horizontal error with 27% and the vertical error by 56%. For the complex variant, these reductions are 25% and 47%, respectively. The various interactions provide further insight into the effects of the tactile displays. We will discuss them in relation to our objectives and hypotheses. The first objective of the present study was to investigate whether a tactile display can help to compensate for the degraded visual information when flying with Night Vision Goggles. To our surprise, the tactile displays result in large performance improvements in both the night vision and the full vision conditions. The latter is not according to our hypothesis. It shows that the positive effect of the tactile displays is so strong that it can even support the pilot under full vision condition. Image quality was also varied by using a rich and a sparse environment. The positive effect of the tactile displays is present in both environments, but indeed larger on the horizontal error in the sparse environment. The third manipulation was the presence of a secondary task (Continuous Memory Task, CMT). For both the horizontal and vertical error, there is a significant interaction between the tactile display and the presence of the CMT. This confirms our hypothesis that the presence of a tactile display reduces the negative effect of adding a secondary task on performance. Without a tactile display, adding a cognitive task results in a factor 2.8 increase of the horizontal error and a factor 1.8 of the vertical error. However, with a tactile display, these factors are only 1.8 and 1.3, respectively. This indicates that a tactile display (or actually adding information) reduces the negative effects of increased cognitive load. Furthermore, although the tactile display increases the amount of information to be processed, the mental effort ratings show that this is not at the cost of higher mental effort. These results confirm the claim that a tactile display presents spatial information intuitively and can be used with low level processing.

The results also show that the differences between the simple and the complex variant are small. Both displays show the same effect on the horizontal error. On the vertical error, the complex variant shows the tendency to be somewhat less effective than the simple variant. Several aspects are relevant here: (1) the usefulness of the extra information that the complex variant presents (i.e., information on the current motion direction) (2) the interaction between tactile signals, which we call tactile clutter and (3) the extent to which the presentation or coding is intuitive. Of course, the first factor and the second and third are like the flipsides of a coin. When the benefit of the additional information is smaller than the costs involved, the complex variant may lead to worse performance than the simple variant. We hypothesize that the critical factor in the present design is tactile clutter. Although the skin is able to process large amounts of (abstract) information -people can read Braille with their fingers- the complex variant may have suffered from the interaction between signals. Adding a moving stimulus may result in a cacophony of tactile stimuli that may result in unpredictable spatio-temporal interactions. Furthermore, the resulting tactile clutter may degrade the intuitiveness of the signals; i.e., some form of processing is required to separate the different components.

This latter is confirmed by the data of the interaction between tactile display and CMT task: with the secondary task present, performance with the simple variant is better than with the complex variant. This indicates that the complex variant has a claim on some form of the higher order processing resources needed in the secondary task. The concept of tactile clutter and the intuitiveness of the coding are both areas that need further research.

Conclusions

This simulator study proves the potential of intuitive tactile torso displays in reducing drift. The display is so effective that it not only results in performance improvement under reduced visual condition, but also under full vision conditions. Also, the presence of a tactile display reduces the performance degradation caused by a secondary (cognitive memory) task. There is no effect of the tactile display on the subjective mental effort rating.

Moreover, the results prove that tactile displays can be applied in fast man-in-the-loop tasks. Finally, advanced tactile displays that are able to present more complex stimuli open up new possibilities of information presentation. This can possibly improve performance, but may also introduce tactile clutter.

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Attitude indicators	Sensory physiology
Cognition	Situational awareness
Cognitive assistance	Space perception
Flight crews	Spatial disorientation
Flight simulators	Spatial information
Human factors engineering	Spatial orientation
Hypergravity	Stimulus (psychophysiology)
Marine navigation	Tactile displays
Motion	Vestibular sense
Motor vehicles	Visual displays
Orientation	Visual perception

14. Abstract

Spatial disorientation (SD), a condition in which the operator fails to sense correctly the position, motion or attitude of the vehicle or of him/herself, continues to be a cause of aircraft accidents, with accident rates that, unlike the overall rate, have not fallen over the past 15 years. The Symposium was convened to review current knowledge of the causes of SD and preventative measures, applicable to air, land and maritime environments. Thirty two oral and 14 poster presentations covered the following topics: Causal mechanisms; Operational and psychophysiological consequences of SD; Incidence of SD in air, land and maritime environments; SD training programmes and training devices; Cognitive and sensory aids for the maintenance of spatial orientation, with an emphasis on the use of tactile cues.

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