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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*”

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 WWI demonstrated that in the absence of vision man really 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 somatogavic 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 Nuttall 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)

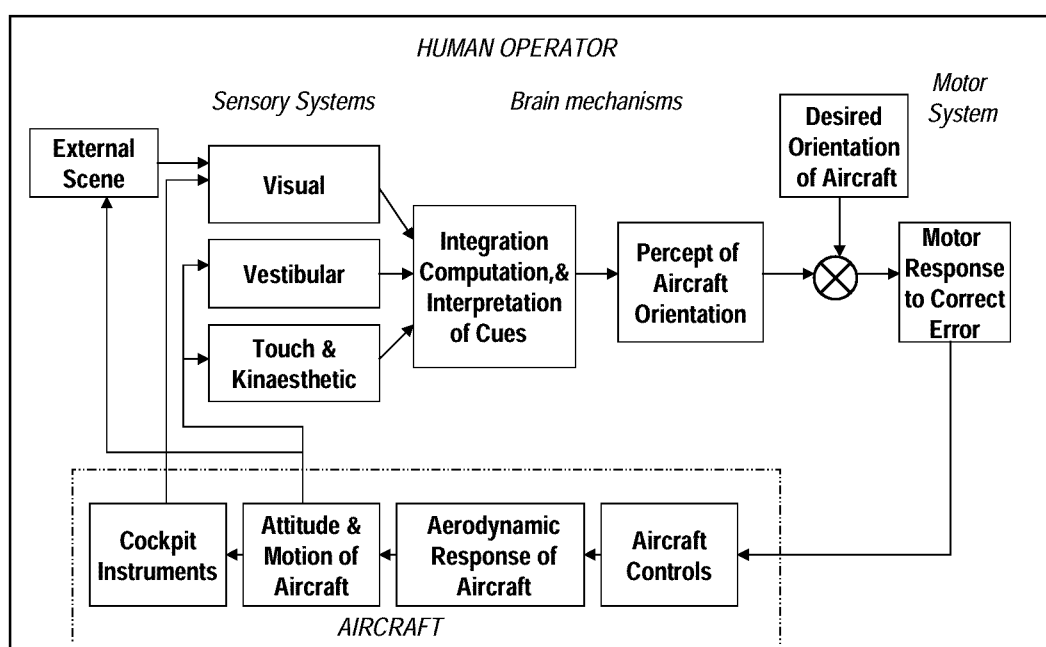


Figure 1, Block diagram of closed-loop, control of aircraft spatial orientation. The pilot receives feedback from vestibular and kinaesthetic receptors, stimulated by angular and linear accelerations, that are phase advanced on the velocity and displacement of visual cues.

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.

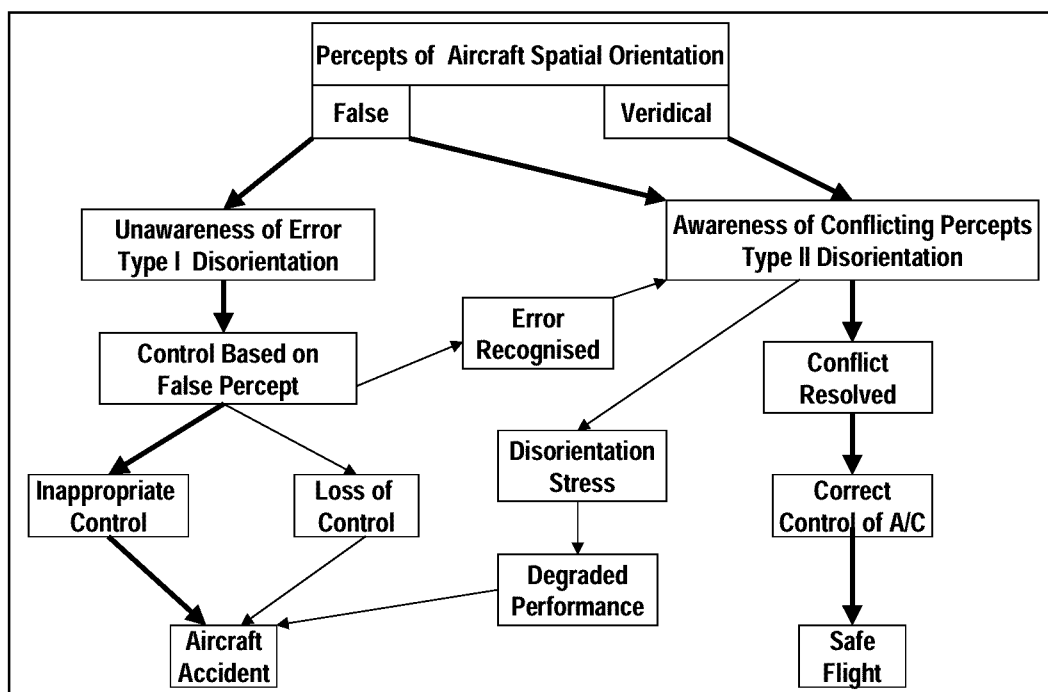


Figure 2. Diagrammatic representation of how Type I and Type II spatial disorientation can effect the pilot's control of the aircraft

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.

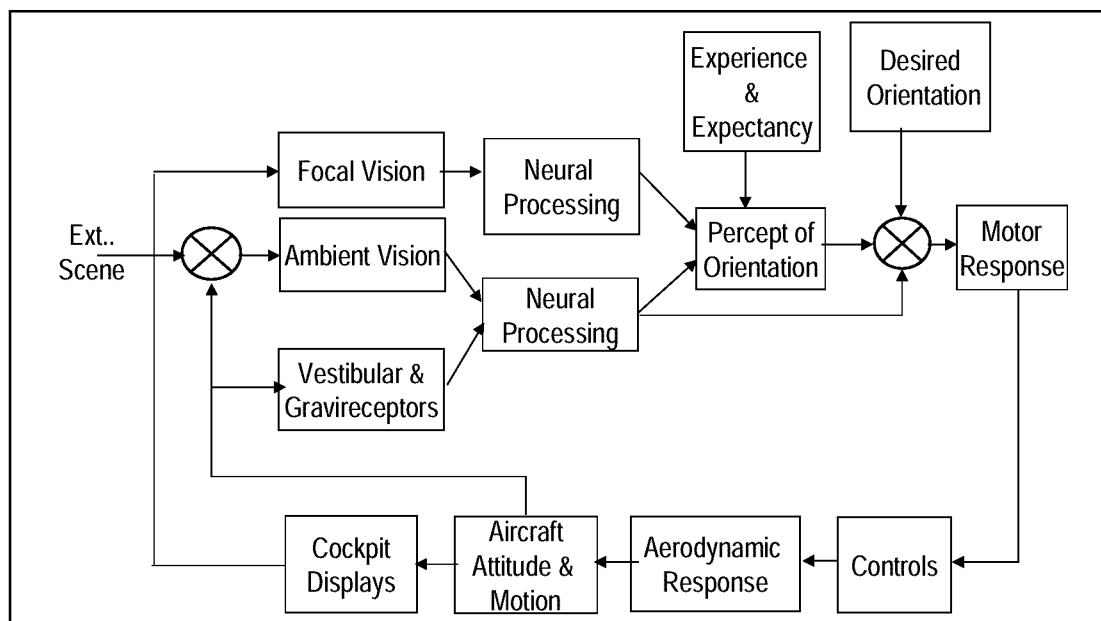


Figure 3. Block diagram of closed-loop control of aircraft spatial orientation to illustrate the separate functions of the focal and ambient visual systems. It is suggested that inputs from the ambient visual and vestibular receptors share a common pathway and neural centre for the processing of afferent 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.

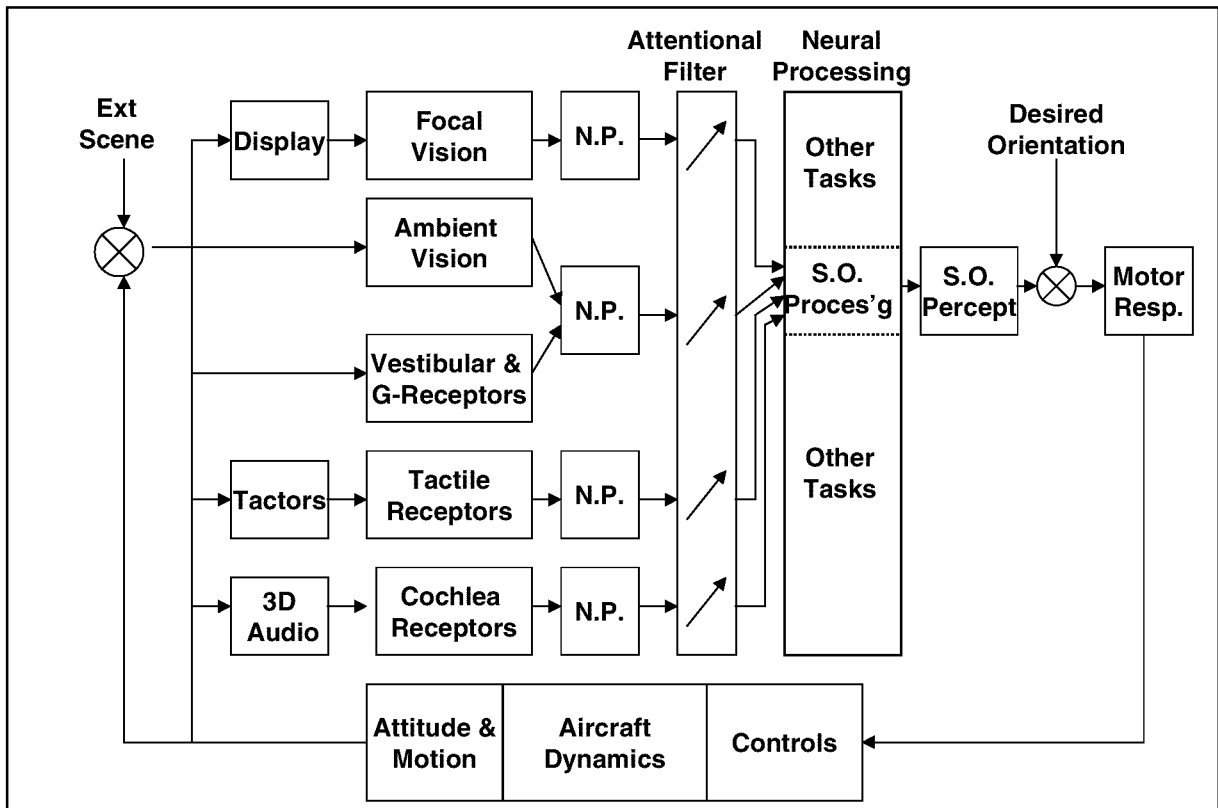


Figure 4. Block diagram of closed-loop control of aircraft spatial orientation (S.O.) to illustrate possible pathways for the neural processing (N.P.) of afferent sensory information, and the presence of a filter that restricts conscious access in conditions of high task load (coning of attention)

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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