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The G Transition Effect Revisited – A Broader Flight Safety Threat than 'Push-Pull'

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Executive Summary

The term 'Push-Pull Effect' (PPE), popularized in the last few years, has been used to describe observed reductions in G-tolerance during acceleration that was preceded by exposures to hypogravity (i.e. <+1Gz). The phenomenon can be easily interpreted as occurring only in classical 'bunt-then-pull' maneuvers. However, our review of previous research and operational evidence suggests a much broader spectrum of at-risk situations and adverse physiological and psychophysical effects. This complex phenomenon is not new, it was observed as early as 1953. It is suggested that the term 'G-transition effect' (GTE) more appropriately describes this phenomenon.

Flight safety implications range from reductions in Gz-tolerance in a variety of scenarios to associations with disorientation and to confounding the results of centrifuge-based research (on which most current G-protection strategies were based). This report provides an overview of past and current research efforts supporting this broader concept of GTE. Of particular note, it seems that the organ of balance (i.e. the vestibular system, one of the components of the 'inner ear' that detects angular and linear acceleration) has significant influence on Gz-tolerance. Furthermore humans may be less able to compensate for whole body roll rotation (rotating sideways like a cartwheel) than pitch rotation (falling forwards or backwards).

Operational scenarios likely to yield potentially dangerous GTE (e.g. point or unloaded barrel-rolls followed by 'pull') are discussed, as are two recent aircraft mishaps where GTE is implicated. It is recommended that:

- Aircrew and other key personnel are educated about the broad range of scenarios at risk for hazardous GTEs.

- Design of G-protective strategies (e.g. electronic G-valves) takes into account not just hypogravity-to-hypergravity transitions, but instead the entire G-time history of exposures.

- In the course of aircraft mishap investigation, the latter should also be scrutinized in looking for the contributing factors of reducing Gz-tolerance and associated disorientation.

- Future research should focus on the effect of how G-time history affect the reduction of Gz-tolerance and the effect of G-transition related disorientation on subsequent performance.

Key words: G-transition, acceleration, spatial disorientation

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Introduction

The term 'Push-Pull Effect' was popularized in the aeromedical community in 1994 (1) and in Canadian Forces (CF) Flight Safety literature in 1995 (2). It was used to describe the reduction of Gz-tolerance when acceleration was preceded by an exposure to hypogravity, i.e. less than +1.0 Gz (sometimes also called 'relative negative Gz'). It is not uncommon to interpret these hypogravity situations as occurring only in the classical 'bunt-then-pull' (i.e. stick pushed forward, then pulled back) maneuvers. However, some evidence suggests that such a narrow interpretation of this phenomenon may inadequately account for the broad spectrum of at-risk scenarios and the wide range of adverse effects that may ensue. Literature review indicated that the physiological and psychological effects of G-transition were observed as early as 1953.

The term, 'G-transition effect' (GTE) more appropriately describes this phenomenon. It consists of a spectrum of physiological and psychophysical effects induced by rapid changes in gravitoinertial forces, alternating between hypogravity (less than +1.0Gz) and hypergravity (greater than +1.0Gz), in 3-dimensional space. The GTE appears to influence the cardiovascular system and the orientation system (which includes vestibular, visual, and somatosensory elements). More importantly, recent evidence suggests that an interaction between the vestibular and cardiovascular systems (called the vestibulo-sympathetic reflex) play a major role in cardiovascular compensation during orthostatic stress[1].

As we review past findings and continue to learn more about this G-transition phenomenon, the limitations of simple categorization of this complex reaction (such as that often understood by the term 'Push-Pull Effect') become more apparent. This report reviews past and current research efforts, Coriolis effects that potentially confound the acceleration knowledge base, relevant accident and incident narratives, disorientation associated with G-transition and operational impact of GTE. Based on current findings, recommendations are made regarding aircrew training, interim GTE countermeasures, and future research.

[1] Orthostatic stress is the physiological stress induced due to inadequate compensatory responses to the gravitational shifts in blood that occur when a person moves from a horizontal or inverted position to an upright vertical position.

Historical Perspectives

The G transition effect is not a new phenomenon. In 1953, Dr. von Beckh conducted in-flight research and reported that exposure to Gz-transition induced tremendous stress on the cardiovascular system (3, 4). In his study, the pilot dove from about 10,000 feet to about 7,200 feet and pulled out of the dive rather abruptly. This manoeuvre produced a positive acceleration of about +6.5Gz, causing blackouts in some of the pilots. Immediately after the pullout, the aircraft was flown to achieve hypogravity by following the ascending arc of a parabola in which aerodynamic forces were equalized by the power of the engine. Dr. von Beckh's findings can be summarized as follows:

(i) The effects of pre-hypogravity acceleration (i.e. 'pull' followed by 'push') resulted in:

- Extended duration of blackouts that occurred during the initial +6.5Gz 'pull' (if the pilot succumbed to blackout).
- Pronounced disorientation due to incorrect labyrinthine cues.
- Chest pains.
- Generalized discomfort.

(ii) The effects of post-hypogravity acceleration (i.e. 'push' followed by 'pull' resulted in:

- Reduced Gz-tolerance, i.e. blackout at lower G values and at shorter Gz duration as compared to the control run.
- Reduced efficiency in physiologic recovery mechanisms; subjects experienced higher strain.

Dr. von Beckh referred to the reduced Gz-tolerance and the greater physiological strain as a logical consequence of the transition from hypergravity to hypogravity. Other investigators have also advocated that the recent Gz time history should be included in the design of future electronic microprocessor–controlled G valve system to provide a better Gz protection (3). Regarding G transition related disorientation, von Beckh speculated that it was due to incorrect labyrinth (organ of balance) cues, and could be prevented by the toxic effect of streptomycin on the vestibular apparatus (1).

Forty years later, Lehr et al. (5) and Prior et al. (6) reported that in both centrifuge-based and in-flight experiments, a period of -Gz immediately before pulling +Gz resulted in a more profound fall in arterial blood pressure and by inference, a reduced Gz-tolerance. There were other attempts duplicating the hypogravity-to-hypergravity G-transition. Using the Coriolis Acceleration Platform (CAP), supine subjects were exposed to 'feet-first' linear translation across the diameter of the platform, and a simultaneous rotation of the platform in the subject's roll plane, thus achieving negative-to-positive G-transition. The results also indicated that the subject's Gz-tolerance was reduced when acceleration was preceded by zero or -Gz (i.e. hypogravity). The reaction was named the 'Push-Pull Effect' (7). Another centrifuge study measured the limits of Gz-tolerance elicited by post-hypogravity acceleration (8) and confirmed others' findings that 'push-pull' scenarios cause significant decrease in Gz-tolerance. However, in all the ground-based studies, especially investigations using the centrifuge, it is important to note that there are potential confounding factors of Gx, Gy and Coriolis cross-coupling prior to the onset of increased acceleration that need to be addressed.

A number of flight tests concentrating on the hypogravity-to-hypergravity portion of the G transition effects have also been performed. McCarthy et al. (9) reported that during flight the decrement in established +Gz-tolerance increased with both amplitude and duration of prior exposure to –Gz. Attempts were also made to use in-flight studies (10) to validate centrifuge-based simulation of the G transition effect. Based on subjective visual end-point measurements, it was concluded that there was a significant decrease in Gz-tolerance during post-hypogravity acceleration, and that the reduction in Gz-tolerance in the aircraft is similar to the reduction previously reported in a centrifuge. It should be noted that the particular flight profiles that were used in this study, similar to one of von Beckh's profiles, do not resemble operational manoeuvres. Secondly, as mentioned earlier ground based simulation produced various G vector biases and most significantly, possible confounding factors induced by Coriolis cross coupling.

Factors Potentially Confounding Centrifuge-based Research

As indicated above, ground-based G-transition studies that employ centrifuges (and similar devices) produce various G vector biases (Gx, Gy) and most significantly possible confounding factors of Coriolis cross-coupling[2] prior to the onset of increased acceleration.

[2] The terms "Coriolis effect" and "cross-coupling effects" are both used in referring to the vestibular effect of tilting the head during whole-body rotation. Coriolis effect can occur in flight when an individual rotates his head about one axis, the ω_2 axis, while the aircraft is rotating about another axis, the ω_1 axis. This produces an instantaneous stimulus to the semicircular canals, about a third axis, that can be both disorienting and disturbing. For example: while an aircraft is in a sharp right turn, if the head and body are rolled to the right relative to the aircraft, a false sensation of climb rate may be produced by the cross-coupled stimulus to the semicircular canals. The stimulus can be calculated from vector algebra as the vector cross-product, or cross-coupling, of the ω_1 and ω_2 velocity vectors; hence the popularity of the term "cross-coupled effect".

For example, to provide -Gz exposure, most centrifuges require the orientation of the subject in the gondola or the gondola itself so that the subject's head swings away from the axis of rotation. While the centrifuge begins planetary rotation, the subject's head is reoriented towards the axis of rotation to create the +Gz acceleration. In so doing, significant Coriolis cross-coupling effects are produced. Other techniques could also be employed to provide the initial –Gz exposure: for example, the subject's head could be placed in an initial pitch-down position. However, Coriolis cross-coupling effects cannot be avoided since they are due to the simultaneous rotation about more than one axis – and this is inevitable in centrifuges. Both the perception of spatial rotation and the discomfort associated with such head/body movements are explainable on the basis of the signals processed by a combination of different sets of semicircular canals (detecting angular acceleration) and the otoliths (detecting linear acceleration) of the inner ear.

These confounding effects are a concern in acceleration research because it has been shown that vestibular stimulation can produce changes in blood pressure (11). In particular, Sunahara et al. (12) demonstrated that Coriolis cross-coupling effects caused significant increases in forearm blood flow as measured by venous occlusion strain gauge plethysmography. The increase in forearm blood flow suggests a decrease in sympathetic activity to this vascular bed. The effect of the vestibular Coriolis reaction on forearm blood flow changes in humans was later confirmed by Sinha (13). Johnson further demonstrated that forearm blood flow increases were also observed during pseudo-Coriolis stimulation (14). Vasodilatation (blood flow increases) in the limbs impairs orthostatic tolerance[3], particularly if blood flow is shown to increase simultaneously in the lower limbs.

Recently, Cheung et al. (15) extended Johnson's findings, using laser Doppler flowmetry and an identical motion profile to that used in Sunahara's study. Significant forearm and calf blood flow increases were found simultaneously during Coriolis cross-coupling stimulation. The temporal sequence of the changes in blood flow was consistent within the subjects from trial to trial, but varied across subjects. In other words, humans may have different sensitivity to these Coriolis-induced vascular changes. As mentioned above, limb blood flow increase compromise the ability to withstand orthostatic stress. These findings (11, 12, 13, 14 and 15) may confound previous reports on reduced G tolerance using a ground-based simulator/centrifuge to produce negative-to-positive Gz where simultaneous Coriolis stimulation was unavoidable. In other words, is the reduced G-tolerance a response to Coriolis stimulation, or negative-to-positive G-transition, or both?

[3] Orthostatic tolerance is the ability to tolerate physiological stress induced by gravitational shifts in blood that occur when a person moves from a horizontal or inverted position to an upright vertical position.

Flight Safety Implication: If reduced orthostatic tolerance induced by Coriolis cross-coupling is confirmed in future centrifuge studies to be a significant confounding effect on measuring G-tolerance in the centrifuge, all existing centrifuge-based research findings (on which G-protective technologies are based) could be drawn into question. This potential confounding factor would likely have even more impact on centrifuge-based simulation of any 'push-pull' maneuvers that would yield head movements due to chair or gondola reorientation that is required to produce the G-transitions.

Flight Manoeuvres that are Susceptible to G-transition Effects

Aircrews often regard –Gz exposure as unpleasant and in some air forces such –Gz manoeuvres are prohibited. In fact, analysis of the Gz environment during 1-v-1 air combat manoeuvring in the F-15, F-16 (16), and F-18 (17) indicated that the pilots experienced high peak levels of +Gz, but very little –Gz. However, there are situations in which negative-to-positive Gz-transitions occur in flight. In the fighter world, one of the common ways to regain energy in order to acquire tactical advantage over the opponent involves "unloading" the aircraft from positive-to-negative Gz prior to accelerating. With few exceptions, this manoeuvre involves rolling and pulling the maximum G-forces available. An anecdotal report by Diedrichs (18) suggested that during high G split-S manoeuvres in the A-7, there is a definite deleterious effect on Gz-tolerance when the pilot is subjected to the transition from negative-to-positive Gz. Retrospective analysis of the G metre recording from operational HUD tape revealed that PPE manoeuvres were present during air combat training missions performed by the USAF (19). However, the analysis focused only on the negative-to-positive G-transition. It is of interest to note that the frequency is significantly higher during Air Combat Manoeuvre (ACM) than Basic Fighter Manoeuvre (BFM).

Current research focuses only on the effects of the transition from hypogravity-to-hypergravity. However, during most military flight manoeuvres, hypergravity-to-hypogravity transition often precedes the transition from hypogravity-to-hypergravity. For example, in one accident (Case One, described below), the mishap aircraft underwent a +Gz-loading of 2.3 to 4.6 in 8.5s during a barrel-roll, before the transition from hypogravity-to-hypergravity. The Gz-time history prior to post-hypogravity acceleration is certain to have an effect on subsequent Gz tolerance as suggested by von Beckh (3, 4). In addition, Frasier et al (5) also suggested that the implementation of recent G-time history, as one of the inputs to new microprocessor-controlled G-valve systems would provide better G-protection.

Other flight operations involving G-transitions that could potentially reduced Gz-tolerance are:

- parabolic flight;
- nap-of-the earth in helicopter flight; and
- low level weapon delivery manoeuvres.

Discussion with CF pilots has revealed that CF aircraft do not often execute parabolic flight manoeuvres, therefore they are of little concern. They also revealed that pilots 'bunt-and-pull' less than 5% of all flight time. The execution of an unloaded barrel-roll (in which less than +1Gz can occur for a few seconds), followed by high-Gz loading during Air Combat Manoeuvres (ACM) could be another instance where hypogravity-to-hypergravity transitions can be encountered.

G-transitions are probably not a concern in CF helicopters because of their limited flight envelope. A recent US Navy study by Dr. Shender verified that G-transitions of nap-of-the-earth manoeuvres in current helicopters were not likely to cause a reduction in G-tolerance (20). During a nap-of-the-earth manoeuvre, the major concern for helicopter pilots is "over-torque" of the rotor rather than the 'Push-Pull Effect' (21).

A review of CF aircraft accidents between 1976-95 suggested that 5 Category A accidents (aircraft beyond repair or resulting in fatal injuries) and 2 incidents were shown to involve G-transition prior to the mishap or incidence (22). It was reported that -Gz was induced by bunting (2 cases), unloaded barrel-roll (2 cases), and a jink-out[4] followed by an extension (1 case). The +Gz were initiated by a slicing manoeuvre (4 cases), pullout manoeuvre after dives (2 cases) and a level turn (1 case). However, the review focussed on the negative-to-positive G-transition only; events leading up to post-hypogravity acceleration were not specified. In other words, more than half of all CF accidents suspected to involve the 'Push-Pull Effect' actually involves the more complex GTEs than the classically understood 'bunt-then-pull'.

When a seated subject is rotated at constant velocity about the earth's horizontal axis, blood flow along the longitudinal body axis will be subjected to two force components. One will be the centrifugal force component, which is proportional to the product of the radius of rotation and the square of the angular velocity. The other will be the sinusoidal component of the earth's gravitational field, which will have the value of +1Gz when upright and –1Gz when inverted. The centre of gravity of high performance fighters is located

[4] Jink-out is a manoeuvre where the pilot pushes the stick forward quickly to achieve 0 to –2Gz and hold for 2 or 3 counts. The pilot will initiate an unloaded roll through the horizon to an attitude so that his flight path is perpendicular to the attacking aircraft which minimized the time available for the attacker to achieve guns tracking solution.

somewhere below the seat of the pilot. Physical principles dictate that hypogravity could be induced by a point-roll manoeuvre during level flight (rolling about the longitudinal axis of the aircraft).

The centripetal acceleration experienced at the pilot's head during a point-roll depends on the rate and the radius of rotation (i.e. distance from the eye level of the pilot to the centre of gravity of the aircraft). For example, in the CF18 it varies from 0.8m to over 1m, depending on the height of the pilot's upper torso. If the aircraft executes a point-roll at 90^0/s and at an eye level rotation radius of 0.8m, the centripetal acceleration experienced is –0.2Gz and at a rate of 180^0/s, the centripetal acceleration is –0.8Gz.

Therefore, similar to the 'bunt-then-pull' maneuver, pulling +Gz following a point-roll can result in a hypogravity-to-hypergravity G-transition. Based on previous G-transition studies (3, 4), such a 'point-roll-then-pull' manoeuvre could potentially reduce subsequent G-tolerance as well. Since high performance flight is 3-dimensional, point-roll manoeuvres may consist of a barrel-roll component as well. The GTE during operational flight is thus more complex than previously suggested.

Flight Safety Implication: The spectrum of maneuvers at risk for producing GTE extends beyond simple 'bunt-then-pull'. Roll-induced hypogravity followed by high-G pull, which occurs more commonly in CF flight operations, is at least as capable of causing G-tolerance reduction, and is probably also further complicated by unfavorable vestibular influences on G-tolerance.

Recent Mishaps Involving Point-Roll Manoeuvres

We sought examples of point-roll manoeuvres in recent aircraft accidents that could be implicated in adversely affecting G-tolerance and found one such instance in the 1995 Cold Lake CF188714 accident (23), and another in a recent incident narrative from the US Navy (24).

Case One: CF188714, 5 July 95 (23)

At 08:57 local time, 5 Jul 95, Lynx Razor Lead transmitted a MAYDAY call on guard announcing that Razor Two was down. The mishap aircraft, Razor Two (CF188714), had been engaged with the lead aircraft in a 1 v 1 neutral engagement. The engagement proceeded normally to the point where the mishap aircraft broke off a high-G dive recovery, rolled inverted, and flew into the ground in a near vertical attitude. The accident investigation did not address the number of roll manoeuvres that were performed prior to the final phase of the fatal impact, nor did it acknowledge the physical effect of a near point-roll. The G-time history of this accident, prior to the final impact is illustrated in Figure 1 in the appendix. The ACMRI (Air Combat Manoeuvring Range Information) data are presented in detail at Appendix A, but key features prior to are summarized as follows:

- An initial right barrel roll to 108° right bank beginning with a 13° nose-up attitude at +2.3Gz loading to neutral pitch attitude at +4.6Gz (gaining an altitude of 2500ft).
- The aircraft then left-rolled back to wings-level, transition from +4.6Gz to +0.8Gz with a 13° nose-low pitch, (losing an altitude of 1593ft).
- The aircraft executed a left point-roll to a bank angle of –79°, which was maintained for 2s.
- The left point-roll resumed aggressively at 81.5°/s to an inverted attitude, setting up to pull in behind the lead.
- A transition to a 38° nose-low followed, with an average of +5.1Gz loading.
- The final +6.4Gz split-S turn preceded the steep dive before impact

The aircraft accident investigation board concluded that the pilot of the mishap aircraft experienced G-induced Loss of Consciousness (G-LOC), probably shortly after the +5.1Gz pull. The G-time history of the mishap aircraft included important G-transitions (especially the +2.3Gz to +4.6Gz and the hypogravity induced by the aggressive point-roll) which could have had significant impact on the pilot's subsequent G-tolerance.

<u>Case Two: US Navy T34 Incident, April 99 (24)</u>

A recent US Navy aircraft incident also appears to support the hypothesis that acceleration following a point-roll (rolling about the longitudinal axis of the aircraft) could result in reduced G-tolerance. During an inverted flight manoeuvre in a T-34C, the Instructor Under Training (IUT) in the front seat initiated a 15° pull-up followed by a right aileron roll to the inverted position (a 180° roll) with slightly less than zero G acceleration. Within 5 seconds, the Instructor Pilot (IP) noticed the altimeter rapidly dropping and attitude approaching 30° nose-low inverted. The IUT decided to recover. During the recovery, it was apparent that both IUT and IP experienced G-LOC. The IP recalled an increase in positive G prior to losing consciousness. After the incident, the IP commented that as FA-18 pilots, they were familiar with the well-known impact on G-tolerance resulting from a rapid negative-to-positive Gz-transition. However the IP also remarked that the inverted flight demonstration was not associated with the physiological 'Push-Pull G-LOC'.

It appears that in this occurrence the interpretation of "Push-Pull Effect" was limited to simple 'bunt-then-pull' maneuvers, and were unaware that any scenario resulting in hypogravity (such as this point-roll to an inverted position prior to acceleration) can reduce G-tolerance. A full description of the accident narrative is attached in Appendix B.

Flight Safety Implication: Both of these aforementioned cases probably involved GTE that were produced by maneuvers that are more complex and insidious than simple 'bunt-and-pull'. They are clear signs that 'Push-Pull Effect' needs to be understood and defined in a broader sense so adverse effects can be anticipated and avoided, or otherwise dealt with.

Cardiovascular Responses to Roll versus Pitch Rotation

Considerable evidence from animal and human studies suggests we are less capable to compensate for roll-induced orthostatic stress, and that the vestibular system plays an important role, (through the vestibulo-sympathetic reflex), in compensating for such stresses. The vestibular system responds to gravitational forces and postural changes. These vestibular signals constantly provide the central nervous system with information needed to compensate and to correct for on-going body movements. Therefore, it is reasonable to postulate that the vestibular system might exert a direct influence on the cardiovascular system.

Recent studies in decerebrate[5] cats (25, 26) demonstrated that increases in sympathetic nervous system output are elicited by pitch rotation, but not by roll rotation. These cats also underwent removal of other key structures of the nervous system (e.g. upper cervical root transection, cerebellectomy, baroreceptor denervation, and vagotomy). Bilateral transection of the vestibular nerves in paralyzed, anesthetized cats impaired hypotension compensation (27). The response characteristics of the sympathetic output are similar to those of the otolith organ. The gain of the vestibulo-sympathetic reflexes during pitch rotation is constant across stimulus frequencies and is in-phase with the change in head position, implying that the vestibular influence is primarily of otolith origin. More recently, direct connections between pertinent areas of the brain (i.e. vestibular nuclei, locus coeruleus, and brainstem pathways) controlling the sympathetic nervous system have been mapped (28). Central vestibular neurons had been identified in the medial vestibular nucleus (MVN) where pitch responses predominate, suggesting that the MVN may also be an important relay for information about orientation within the pitch plane (29).

[5] Decerebration is the removal of the brain, sometimes employed in classical physiological experiments where one wants to rule out any response from the nervous system that might confound the results obtained in electrophysiological studies

In humans the evidence is not as clear. Since the early 1900s it has been shown that galvanic or caloric stimulation[6] produced changes in blood pressure (10). This observation has been extended to optokinetic[7], Coriolis, and pseudo-Coriolis[8] stimulation (12). However, these stimuli also provoked nausea and discomfort that could lead to cardiovascular effects (psychologically or otherwise). Recently, clinical observation has indicated that a significant number of patients with peripheral vestibular disease were susceptible to orthostatic hypotension after standing up, following sustained supine posture (30). An immediate increase in Muscle Sympathetic Nerve Activity (MSNA) with head-down neck flexion suggests vestibulo-sympathetic reflex effect (31). Hume and Ray (32) further demonstrated that MSNA increases in magnitude as the degree of head-down neck flexion increases. The MSNA responses were shown not to be due to stimulation of non-specific receptors in the head ensuing increase in cerebral pressure. The change in MSNA is one of the important compensatory mechanisms in maintaining arterial pressure. This data provides support for the influence of the vestibular system on sympathetic outflow in humans.

Roll-Induced Orthostatic Hypotension in Humans

The effects of roll rotation on the cardiovascular system in animals, suggested by the literature reviewed above, have been supported by a recent laboratory study in humans. Using an electronic tilt-table, our study indicated that the rate and magnitude of blood pressure decrease as induced by a 135° head-down (HD, -0.7Gz) to 15° head up (HU, +0.98Gz) manoeuvre is significantly higher in roll than in pitch rotation (33, 34). Simultaneously, the increase in heart rate was significantly greater during pitch than during roll rotation. These results suggest poor cardiovascular compensation for the orthostatic stress (HD-to-HU tilt) during roll rotation, and that pitch rotation is better compensated for. This is not really surprising from an evolutionary standpoint since we develop adaptations according to the needs of daily living: we often pitch forward but seldom have to roll more than 5-10°. Furthermore, roll movements we make are usually limited to head-only. In other words, teleologically[9] we are not "hard-wired" to roll.

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[6] Galvanic stimulation is the electrical stimulation of the organ of balance by placing electrodes around the temporal area. Caloric stimulation is a clinical procedure whereby the outer ear canal is irrigated twice, once with warm water (or air) and once with cold water (or air) and recording the provoked involuntary eye movements to assess the integrity of the horizontal semicircular canals.

[7] Optokinetic stimulation is performed by recording the subject's response (perception of movement or eye movements) as the subject watches a visual stimulus that is moving horizontally, vertically or torsionally.

[6] Pseudo-Coriolis stimulation is induced when a seated subject exposed to a visual stimulus rotating around him, execute head movements out of the plane of rotation of the visual stimulus. It could results in subjects experiencing disorientation and symptoms of motion sickness.

[9] Teleological is the view that developments are due to the design that is served by them.

This tilt-table study had some important limitations: the maximum obtainable angular speed is 45°/s; the post-hypogravity acceleration can never exceed +1Gz; and there is a changing G-vector during roll rotation. Nevertheless, our data suggests that during operational flight, a roll manoeuvre executed during hypogravity-to-hypergravity G-transition could impair subsequent G-tolerance as described by von Beckh (4).

There is other evidence indicating that other forms of vestibular stimulation also affects cardiovascular responses in humans. It was shown that high angular acceleration of the head about the yaw axis reduces the baseline baroreflex[10] responsiveness by 30%, inhibits vagally mediated baroreflex control of heart rate, and impairs orthostatically induced tachycardia[11] (35). High-speed yaw rotation also caused progressive tachycardia, narrowing of pulse pressure, a drop in mean arterial pressure, and inferentially, a drop in cardiac output (36).

Flight Safety Implication: Roll rotation appears to have greater impact on G-tolerance than does pitch rotation. Since rotations about the roll axis tend to be longer and faster and more often encountered than those in pitch or yaw, it is likely that roll poses the greatest threat in terms of GTE.

Disorientation during Prolonged Rotation

Reduced G-tolerance is not the only deleterious effect of G-transition. In von Beckh's study (3), disorientation during the transition from hypergravity to hypogravity, was also reported. However, the type of disorientation that was induced and how it might affect subsequent G-transition and G tolerance remains to be investigated. Surveys of civilian aerobatics pilots revealed that 12.7% reported persistent vertigo after aerobatics flights with manoeuvres involving -Gz (37).

As mentioned above, hypogravity can be induced by point-roll or unloaded barrel-roll. The lack of sensory information about rolling at a constant rate, as well as the erroneous signal of rolling in the opposite direction on recovery from a roll, are well known. Typically, in a roll of 2 radians/s (about 100°/s), the sensation of roll lingers for another 10 to 15s (38). Furthermore the time when the sensation of rotation disappears is considerably shorter in roll than in pitch and yaw (39).

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[10] Baroreflex is a reflex feedback mechanism that operates to stabilize the blood pressure and heart rate.
[11] Tachycardia is the excessive rapidity of the heart's action.

The hydrodynamics and frequency response of the mechanical component of the semicircular canals are well known. Force acting on the cupula is the product of the angular acceleration of the head and the moment of inertia of the endolymph[12] and the cupula[13].

This can be described by the following second-order differential equation:

$$\alpha H = K\theta + \Upsilon d\theta/dt + Hd^2\theta/dt^2$$

Where:

H/Υ = Inertial time constant, latency of cupula deflection;

Υ/K = Elastic time constant, exponential time course of cupula return;

H = moment of inertia of endolymph and cupula, coefficient of (mass-dependent) resistance

K = Coefficient of elastic (position-dependent) constant;

Υ = Coefficient of viscous (velocity-dependent) constant,

θ = Angular displacement of endolymph and cupula.

During a prolonged turn with steady angular velocity, the elastic force acting against the heavy viscous damping gradually restores the cupulae to their neutral position. When the turn is stopped suddenly, the cupulae are initially deflected through angles equal-but opposite-to those of the original angular velocity of the turn. Subsequently, their elastic properties again restore them along an approximately exponential time course to their neutral position. The effective (elastic) time constant of post-rotational decay (as measured by the post-rotational sensation and the time course of compensatory eye movements), are considerably shorter in roll than in pitch and yaw (39).

In the context of aviation, this implies a considerably greater rate of error development in response to roll stimuli than to pitch and yaw. For example, if a pilot rolls an aircraft from 80° left to 80° right in 4s (assuming that the angular velocity in roll is 40°/s throughout), the apparent angular velocity just before stopping would have fallen exponentially to 21°/s. On completion of the manoeuvre it would appear to the pilot that he had rolled through 117°, leaving him in an apparent 37° bank to the right.

Flight Safety Implication: Perception of roll rotation is poor in humans and gets worse if the rotation is prolonged. The misperception of roll rotation might alter the intended attitude of the aircraft during subsequent G transition.

[12] Endolymph is the fluid within the membranous labyrinth of the semicircular canals.

[13] Cupula is the gelatin-like partition within the expanded portion of the semicircular canals where the hairs of the sensory cells are embedded.

Conclusions

It may be concluded that GTE potentially impacts upon flight safety in the following ways:

G-tolerance is probably reduced not only by the hypogravity (< +1Gz) of 'bunt-than pull' manoeuvres, but also by the roll-induced hypogravity of point- and unloaded barrel-rolls. G-tolerance in the aforementioned manoeuvres are likely also complicated by recent Gz-time history and vestibular (inner ear) influences. Current understanding of the GTE threat may be limited to simple and less frequently encountered 'bunt-then-pull' scenarios, rather than the much broader spectrum of at risk manoeuvres.

Roll rotation appears to have a greater impact on G-tolerance than does pitch rotation. Since rotations about the roll axis tend to be longer and faster and more often encountered than those in pitch or yaw (in fixed-wings), it is likely that roll poses the greatest threat in terms of GTE.

Coriolis cross-coupling that occurs inevitably in the centrifuge may confound research findings and therefore may draw into question many existing and future conclusions from centrifuge-based studies especially during 'Push-Pull profiles.

Disorientation is prevalent during G-transition from hypergravity to hypogravity. Secondly during 'roll-then-pull' manoeuvre, misperception of roll especially during prolonged roll rotation (in seconds) could affect the intended attitude for the subsequent G transition.

Recommendations

It is recommended that:

- Any aircrew involved in high-G operations (and important support personnel such as aeromedical instructors and flight surgeons) should be educated about the broad scope of GTE threat, and the at risk manoeuvres. In particular, awareness of the possibility of vestibular influences on G tolerance should be raised.

- In mishap investigation, particularly those suspected to involve significant G-exposure or disorientation, attention should be paid to the entire G-time history, specifically looking for episodes of hypogravity or prolonged roll that may suggest GTEs.

- Future research and development should take GTEs into account. In particular, electronic G-valve control algorithms currently under development should allow for GTEs. G tolerance training should include G transition manoeuvres. Centrifuge or other ground-based facilities designed to simulate G-transitions should account for the potentially confounding effects of Coriolis cross-coupling. Finally, further research should be directed at investigating the interaction between GTEs and spatial disorientation.

Acknowledgements

The authors wish to thank Capt Wayne Wong for his meticulous analysis of the ACRMI data on the final flight path of the CF188714 accident, invaluable discussions with LCol Al Stephenson, pilots from the 410 CF-18 Tactical Training squadron, CF-18 standards pilot Maj Steve Wills, Capt Pat Barnes, and former accident investigator Capt Mike Brush.

Appendix A. Analysis of the final flight path of CF-188714 accident, 5 July 1995, based on ACRMI data

1. At 08:57 local time, 5 Jul 95, Lynx Razor Lead transmitted a MAYDAY call on guard announcing that Razor Two was down. The mishap aircraft Razor Two (CF188714) was engaged with the lead aircraft in a 1v1 neutral engagement. The engagement proceeded normally to the point where the mishap aircraft broke off a high G dive recovery, rolled inverted, and flew into the ground in a near vertical attitude.

2. Based on the ACMRI (Air Combat Manoeuvring Range Information) data from the accident investigation report referenced above, Capt. Wayne Wong (a former instructor pilot from Moose Jaw) performed a detailed analysis on the final flight path prior to ground impact. This ACMRI data was obtained from a wingtip P-4 pod sent to a ground station which rotated and translated the information to the aircraft's centre of gravity. All G-loading information is accurate to ±0.5G, and roll rates are accurate to 15% of the given readings. The events from the time between visual contact of the pilots of the two aircraft during the 1v1 neutral engagement and the proposed time that the pilot of the mishap aircraft impacted the ground are summarized as follows:

3. Initially the pilots of both aircraft were approaching each other head-on and had visual contact with one another. Razor Two was approximately 2000' higher than Razor Lead. Subsequently Razor Lead lost sight of Razor Two. During that transmission Razor Two entered a right barrel-roll from an upright position at 08:54:59.62 to a maintained bank angle of 108 degrees at 08:55:08.12. At this time Razor Two stated that he still had Razor Lead visual and called to continue the engagement. During this interval the aircraft began the sequence in a 13° nose-up attitude at a +Gz-loading of 2.3. By the end of the 8.50 seconds the aircraft was in a neutral pitch attitude at a +Gz-loading of 4.6. This portion of data suggests a barrel-roll during this segment of the flight due to the increase in +Gz-loading throughout the manoeuvre and the increase in aircraft altitude from 20703 ft ASL to 23210 ft ASL:

08:54:59.62 5° right	08:55:02.82 46° right	12.8°/s for 3.2s right roll
08:55:02.82 46° right	08:55:08.12 108° right	11.7°/s for 5.3s right roll

4. Razor Two then rolled back to a wings-level position. The roll to wings-level was completed at 08:55:15.32. In this instance the manoeuvre began with a +Gz load of 4.6 which reduced throughout the roll to a +Gz load of 0.8 by the end with the aircraft in a 13° nose-low pitch attitude and a loss of altitude from 23210 ft ASL to 21617 ft ASL:

08:55:08.12 108° right	08:55:10.32 95° right	5.9°/s for 2.2s left roll
08:55:10.32 95° right	08:55:12.42 71° right	11.4°/s for 2.1s left roll
08:55:12.42 71° right	08:55:13.32 55° right	17.8°/s for 0.9s left roll
08:55:13.32 55° right	08:55:15.32 20° left	28.5°/s for 2.0s left roll

5. At 08:55:15.32 the aircraft continued a left roll to maintain a bank angle of -79° by 08:55:20.12. This was close to a point-roll since the G-loading throughout the manoeuvre varied between a + Gz load of 0.8 to 0.0. The manoeuvre concluded with the aircraft in a 20° nose-low pitch attitude with a loss of altitude from 21617 ft ASL to 20687 ft ASL:

08:55:15.32 2° left	08:55:15.72 80° left	15.0°/s for 0.4s left roll
08:55:15.72 8° left	08:55:16.22 12° left	8.0°/s for 0.5s left roll
08:55:16.22 12° left	08:55:16.72 12° left	PAUSE for 0.5s
08:55:16.72 12° left	08:55:17.22 16° left	8.0°/s for 0.5s left roll
08:55:17.22 16° left	08:55:17.82 27° left	18.3°/s for 0.6s left roll
08:55:17.82 27° left	08:55:18.02 31° left	20.0°/s for 0.2s left roll
08:55:18.02 31° left	08:55:18.62 46° left	25.0°/s for 0.6s left roll
08:55:18.62 46° left	08:55:19.12 58° left	24.0°/s for 0.5s left roll
08:55:19.12 58° left	08:55:19.52 67° left	22.5°/s for 0.4s left roll
08:55:19.52 67° left	08:55:19.62 69° left	20.0°/s for 0.1s left roll
08:55:19.62 69° left	08:55:20.12 79° left	20.0°/s for 0.5s left roll

6. The mishap aircraft then paused in this banked configuration for 2.0 seconds, during which time the aircraft dropped from 20687 ft ASL to 20140 ft ASL and the +Gz level varied from 0.3 to 1.6. The pilot then rolled inverted. This roll began at 08:55:22.12 and was completed at 08:55:23.42 with a slight degree of barreling because the +Gz level varied from 2.8 near the beginning of the manoeuvre to 0.1 by the end. The pitch attitude transitioned from 20 to 32 degrees nose-low during this portion of the manoeuvre and the aircraft fell from 20140 ft ASL to 19621 ft ASL:

08:55:22.12 72° left	08:55:22.42 96° left	80.0°/s for 0.3s left roll
08:55:22.42 96° left	08:55:22.52 108° left	100.0°/s for 0.1s left roll
08:55:22.52 108° left	08:55:22.82 144° left	120.0°/s for 0.3s left roll
08:55:22.82 144° left	08:55:22.92 155° left	110.0°/s for 0.1s left roll
08:55:22.92 155° left	08:55:23.32 182° left	67.5°/s for 0.4s left roll
08:55:23.32 182° left	08:55:23.42 185° left	30.0°/s for 0.1s left roll

7. At this point Razor Two stopped his roll, maintained an inverted position for 0.4 seconds, and at 08:55:23.82 proceeded to pull in behind Razor Lead, transitioning to a 38° nose-low attitude by 08:55:31.32, accomplishing the manoeuvre in 7.5 seconds with an average +Gz-loading of 5.1. A +Gz level above

5.0 was maintained for 5.5 seconds from 08:55:25.02 to 08:55:30.52. The pilot started with a +Gz load of 1.2 and pulled to a maximum +Gz level of 6.4 during this portion of the flight and the aircraft descended from 19621 ft ASL to 14672 ft ASL:

08:55:23.82 185° left	08.55:31.32 10° right	PULL ONLY - NO ROLL

8. During the later stages of this pull out it is believed that the pilot lost consciousness. The aircraft commenced a right roll back into an inverted position between 08:55:31.32 and 08:55:35.42 just as the +Gz level was falling below 5.00. There was no logical reason to consciously roll inverted once again because Razor Two had a very offensive position on Razor Lead, and was winning the fight. The investigation board's findings stated that this was "a tactically unsound manoeuvre". Razor Two was barrel rolling for 4.1s at an average of +3.7Gz thus causing massive asymmetric loading on the airframe while rolling at an average rate of 39.0 °/s. The aircraft's pitch attitude dropped from 38 degrees nose low to being pointed directly at the earth during this barrel roll while the altitude fell from 14672 ft ASL to 12353 ft ASL:

08:55:31.32 10° right	08:55:33.52 112° right	50.9°/s for 2.2s right roll
08:55:33.52 112° right	08:55:35.42 170° right	30.5°/s for 1.9s right roll

9. Razor Two's +Gz level then dropped off to between 1.0 and 2.0 and the aircraft ceased to roll for the remainder of the flight. At 08:55:45.42 the investigation board believes Razor Two regained consciousness and attempted a rapid pull to +7.5Gz in an effort to avoid the ground. Impact occurred at 08:55:47.62 at an indicated airspeed of 723 knots. The time elapsed between the completion of the final rolling manoeuvre and the time of impact was 12.2s. The altitude plummeted from 12353 ft ASL to ground level. The ACMRI data is no longer valid after 08:55:46.12 due to the inaccuracies created by the position of the impact sight on the range and the fact that the closest range acquisition sight was not operational.

10. The events described from A3 to A9 is time-stamped on the attached figure of G loading and onset.

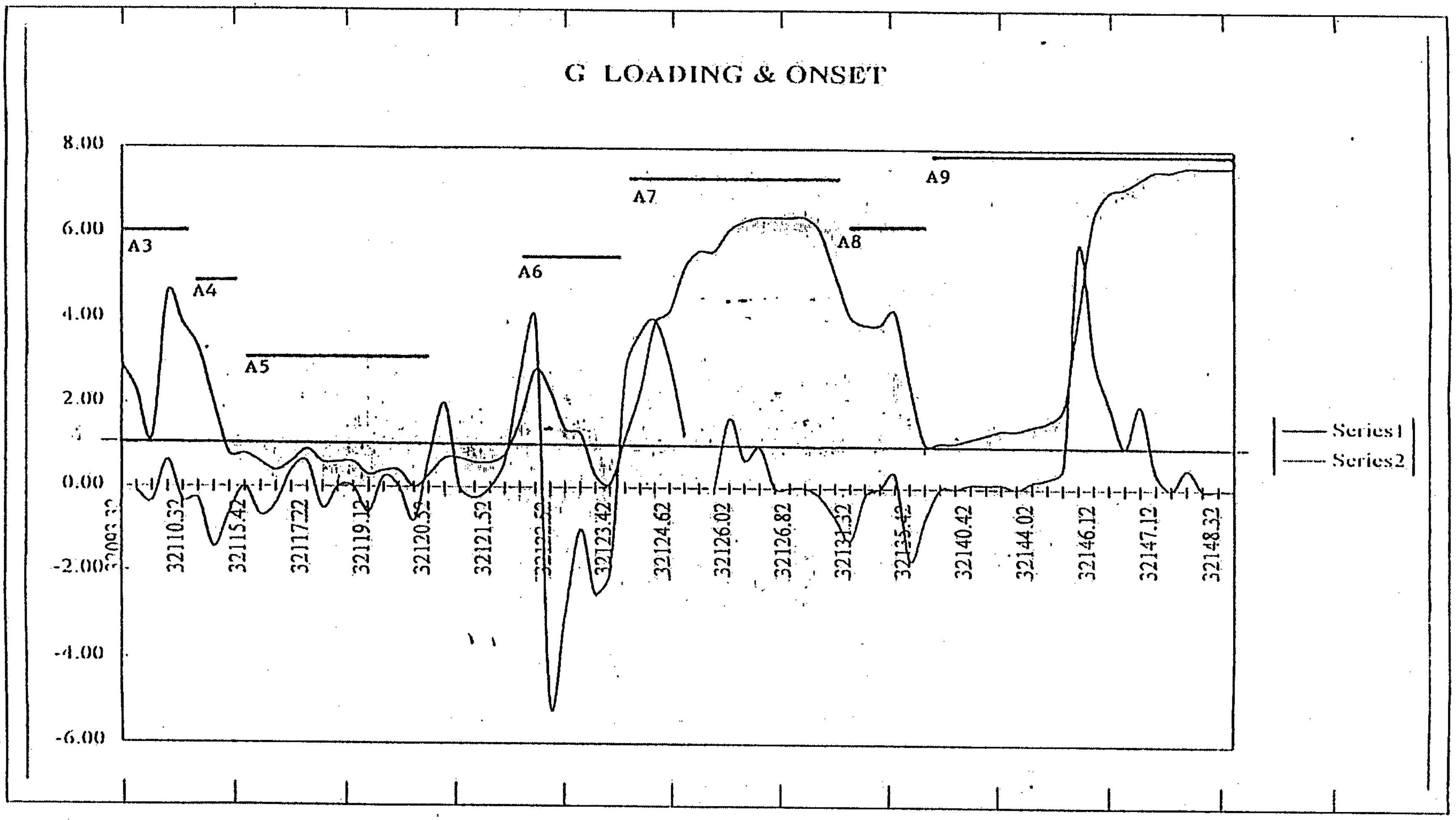

Figure 1.
Series 1(top trace) indicating the Gz level vs. total elapsed time prior to the mishap, horizontal bars (A3, A4, A5 etc.) indicating the time interval corresponding to the description in Appendix A, paragraph 3, 4, 5, etc.

Appendix B

1. This report concerns a routine hazard to naval aviation. Risk code II, endorsement not required. Summary: Pilots experienced GLOC during unusual attitude recovery.

2. Data

A. Aircraft: (1) T-34C, (2) 160490, (3) 490, (4) VFA-125

B. Equipment: N/A

C. Environment: (1) 16Apr99, (2) 1140L, (3) TANGO, (4) Day, (5) N362000, Foothill 2 MOA, (6) CAVU

3. Circumstances

A. Origin: NAS Lemoore, CA

B. Mission: DAWG-2 IUT

C. Flight purpose code: 1A1

D. Type of flight plan: VFR

E. Destination: NAS Lemoore, CA

F. Aircraft evolution: (1) Inverted flight manoeuvre, (2) 150KIAS, (3) 330 magnetic, (4) 5500 AGL, (5) 7500 MSL, (6) 7500 Ft, (7) 0 (plus sign) 05, (8) 1 (plus sign) 00, (9) 0.

G. Narrative: At 150 KIAS and 7500 ft MSL, IUT in front cockpit began an inverted flight manoeuvre by initiating a 15 degree pull up followed by a right aileron roll to the inverted position with a slightly less than zero G. IP in rear cockpit noted altimeter at 7800 ft MSL and airspeed at 120 KIAS after 180 degrees of roll. Within 5 seconds of initiating the manoeuvre, IP noticed the altimeter rapidly decreasing and attitude approaching 30 degrees nose low inverted. IUT stated (quote) This isn't working, I'm going to recover (End quote). The last thing the IP recalled was an increase in positive G, attitude greater than 60 degrees nose low inverted, and 220 KIAS. IUT began a recovery by rolling wings level toward the nearest horizon. The last thing the IUT recalled was a 30 degree nose low upright attitude, five degrees right wing down, with the nose tracking tooward the horizon. The next thing the IUT or IP recalled was the aircraft in a 15 degree nose high upright attitude, 25 degree right wing down, with the nose continuing to track up. IUT realized he had experienced a GLOC and stated (Quote) Do you have it? (End Quote) to the IP, questioning him as to whether he had control of the aircraft. IP then realized he had also experienced a GLOC. IUT initiated a recovery from the ensuing nose high unusual attitude and informed the IP they were returning to base. The forward cockpit G meter read 5.2G's. Aircraft returned to base uneventfully.

4. Corrective action

A. For SFWSPAC: brief this hazard to all pilots and discuss the effects of rapid G onset.

B. Discuss the effects of negative to positive G-transition

C. For all mentor aircraft activities: discuss the items covered under SFWSPAC corrective action.

5. Remarks: None.

6. Point of contact: LCDR Bradley Burgess, safety officer, SFWSPAC, bburgess@sfwspac.lemoore.navy.mil, DSN949-1143/Comm (550\9) 998-1143.

7. Commanding Officer comments: As the IP of this flight, my experience and my student's as FA-18 pilots gave a keen understanding of the hazards associated with high G manoeuvres; specifically, GLOC. The aviation physiology course at NAS Lemoore which we both attended, accurately describes the well-known impact on G-tolerance resulting from rapidly going negative to positive G. Despite this background, our briefed manoeuvre (inverted flight demonstration) was not associated with the physiological phenomenon of push-pull GLOC. Such oversight proved extremely hazardous in this case. Adherence to the briefed altitude, airspeed and trim criteria for setting up the demonstration was key to the ultimate outcome of this evolution. Without pilot control, the aircraft completed the final portion of the recovery, seeking the trim airspeed of 150 knots. The excess 5000 feet altitude allowed my student and I enough time to recover from the debilitating effects of GLOC. Having conducted several inverted flight demonstrations as both an IUT and IP, I never experienced anything akin to this incident. Still, the T-34C is an acrobatic capable aircraft, and no portion of the flight envelope should be considered without risk. Aircrews must take a hard look at all aspects of every portion of their flight and mitigate associated hazards, even those evolutions that seem benign in the extreme.

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The term 'Push-Pull Effect' (PPE), popularized in the last few years, has been used to describe observed reductions in G-tolerance during acceleration that was preceded by exposures to hypogravity (i.e. <+1Gz). The phenomenon can be easily interpreted as occurring only in classical 'bunt-then-pull' maneuvers. However, our review of previous research and operational evidence suggests a much broader spectrum of at-risk situations and adverse physiological and psychophysical effects. This complex phenomenon is not new, it was observed as early as 1953. It is suggested that the term 'G-transition effect' (GTE) more appropriately describes this phenomenon.

Flight safety implications range from reductions in Gz-tolerance in a variety of scenarios to associations with disorientation and to confounding the results of centrifuge-based research (on which most current G-protection strategies were based).

This report provides an overview of past and current research efforts supporting this broader concept of GTE. Of particular note, it seems that the organ of balance (i.e. the vestibular system, one of the components of the 'inner ear' that detects angular and linear acceleration) has significant influence on Gz-tolerance. Furthermore humans may be less able to compensate for whole body roll rotation (rotating sideways like a cartwheel) than pitch rotation (falling forwards or backwards).

Operational scenarios likely to yield potentially dangerous GTE (e.g. point or unloaded barrel rolls followed by 'pull') are discussed, as are two recent aircraft mishaps where GTE is implicated. It is recommended that:

- Design of G-protective strategies (e.g. electronic G-valves) takes into account not just hypogravity-to-hypergravity transitions, but instead the entire G-time history of exposures.

- In the course of aircraft mishap investigation, the latter should also be scrutinized in looking for the contributing factors of reducing Gz-tolerance and subsequent disorientation.

- Future research should focus on the effect of how G-time history affect the reduction of Gz-tolerance and the effect of G-transition related disorientation on subsequent performance.

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G transition, acceleration, spatial disorientation, hypoggravity, hypergravity

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