Training as a Countermeasure for Spatial Disorientation (SD) Mishaps: Have Opportunities for Improvement Been Missed?

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1.0 INTRODUCTION

Dangerous episodes of spatial disorientation (SD) in reference to the gravitational upright can be caused by various clinical balance pathologies or by unusual combinations of visual, vestibular, and/or somatosensory input to normal, healthy sensorimotor systems. When SD occurs, falling or vehicle accidents follow, resulting in expense, injury, and death. The risk of mortality after a fall is high among elderly people and SD during flight is a leading case of fatal aviation mishaps. During flight, SD occurs whenever a pilot fails to correctly interpret his/her aircraft's attitude, altitude, or airspeed in relation to ground or significant objects[1].

SD is the leading aeromedical cause of fatal human error-related aircraft accidents [2];[3]. Despite this, SD has been an unsolved problem since the birth of flight [4]. Once it was understood that the vestibular organs were uniquely implicated in motion sensing and SD, it was logical to suppose (as with clinical vertigo) that a healthy vestibular system would be critical for avoiding SD. This did not prove to be true [5];[6]. While certain kinds of vestibular pathology make SD more likely, SD occurs readily among pilots with a normal vestibular system. SD is no longer considered an abnormal response; rather, SD is recognized as a normal response to an abnormal stimulus.

SD is both common and insidious. SD is a causal factor in at least 25% of all aircraft mishaps [3], but Durnford, DeRoche, Harper, and Trudeau (1996) estimated that approximately 80% of aircrew have experienced SD, with 43% of participants reporting that they were not immediately aware of being disoriented. This type of SD is called unrecognized (or Type I) SD, and it makes SD particularly dangerous.

Durnford et al., Gaydos, Harrigan, and Bushby (2012) confirmed that SD is an important contributor to rotary wing mishaps in the U.S. Army. Gaydos et al. (2012) estimated that 11 percent of mishaps between the years of 2002 and 2011 were attributable to SD, which is an average of 10 SD accidents per year. Moreover, Gaydos et al. pointed out that, contrary to popular belief, the number of accidents caused by SD was not decreasing over the years.[1] Finally, they asserted that SD is under-reported as many accidents are simply categorized more generally as human error when unrecognized SD occurs.

A NATO RTO report (2002) described the problem of brownout, a key SD contributor that occurs when a rotary-wing aircraft causes dust or sand to lift from the ground, creating a degraded visual environment (DVE) [9]. Not only can blowing dust, sand, snow, or water obscure the pilot's vision, it also may drift in ways that could induce a dangerous illusion of self-motion known as vection [10]. Brownout was a consistent problem during the recent conflicts in Iraq and Afghanistan and SD increased as a result, with approximately 75% of cases of SD occurring under conditions of DVE [9]. SD due to DVE or DVE-induced vection also could occur when hovering over blowing snow (whiteout) or water, with equally deleterious consequences [11]. NATO RTO (2002) explains that when a DVE occurs, pilots are forced to rely on cockpit displays (rather than out-the-window visual cues) to alert them of their position relative to the terrain below. Unfortunately, their visual attention and cognitive processing is often distracted or overloaded, so they may fail to attend adequately to a small visual display such as an attitude indicator, additionally there is limited drift information in a standard instrument panel..

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[1] This sentiment is consistent with Gibb et al., 2011, who said "…almost three decades later [after the release of a key educational video], the aviation community still has not substantially reduced the likelihood of SD-related mishaps." (p. 1)

2.0 SOME APPROACHES THAT HAVE BEEN ATTEMPTED TO COUNTER SD

Three traditional categories of SD countermeasures have been tried since the inception of human flight, with mixed results; they are shown in Table 1 and discussed in this section. They divide into approaches focused on identifying pilots insusceptible to SD, providing helpful sensory cues to pilots to prevent SD mishaps, and training pilots to avoid and survive SD. Each approach will be discussed, but SD training methods (and needed training improvements) will be the main focus of this report.

Table 1. Main approaches that have been tried to prevent SD during manually-controlled, manned flight.[2]

	Clinical Selection	Orienting Display	Training
Main Advantage	Proven in many other domains of military performance	Has the potential to eliminate SD during manned flight	Relatively fast and inexpensive to implement
Main Disadvantage	Limited success so far in preventing SD	Requires prolonged RDT&E[2] and formal acquisition	Most SD occurs without conscious recognition
Current Status	No longer used formally[3]	Many of the most promising solutions are still in development	This has been implemented but could be improved

2.1 Selection

Personnel selection was an early countermeasure that was attempted to prevent SD among pilots. According to Benson (2002), during the early 20th century, the evidence indicated that some mishaps involved spins or spirals and that a blindfolded deaf person[4] did not perceive aircraft motion normally. Such observations contributed to the use of the Bárány[5] chair during pilot selection, to confirm normal functional vestibular responses to rotation. This approach was consistent with other, fairly successful approaches intended to identify pilots with the most suitable cognitive or psychomotor abilities, but it was later realized that while vestibular pathology renders vertigo more likely, SD occurs readily among pilots with normal vestibular function. While SD selection for vestibular function is not an active countermeasure anymore, individual cognitive contributors to SD and cognitive effects of (recognized) SD have received some attention [12];[13]. It is possible that such cognitive findings may augment certain aspects of SD training in the future.

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[2] Research, Development, Testing, and Evaluation

[3] No formal ground-based selection for SD susceptibility is done, but simple office tests of balance are done to confirm overall health, and failure to adapt to airsickness during flight training can lead to disqualification.

[4] Since the early observations of William James, it has been known that such persons often lack normal vestibular function.

[5] Named after the Nobel Laureate Robert Bárány and sometimes wrongly referred to as the “Barney” chair (perhaps because the name is pronounced “Bah-rah-nee,” which could become contracted to “Bahrnee” in speech).

2.2 Orienting Displays

Starting with flight instruments such as the attitude indicator, displays to aid pilots have been an active area of development. More recently, sophisticated heads-up and head-mounted displays have been developed with various features, including forward-looking infrared vision, conformal scene references, projected flight paths, look-through airframe capability, etc. While these displays have provided increased information to the pilot over the years, they have not always reduced the likelihood of SD. For example, night vision devices have aided many missions that would have been impossible without them, but flying with night vision goggles has been recognized as a situation more likely to induce SD than to prevent it [6]. In fact, the majority (65%) of SD-related helicopter mishaps occur while employing a night vision aid [8].

How can it be that giving pilots more visual information about the environment still allows them to become disoriented? A consideration of how orientation of the self is maintained accurately during normal terrestrial locomotion may be helpful to answering this question. During the normal terrestrial locomotion style that humans evolved, we derived our sense of self-versus-substrate in a number of ways which contrast markedly with the way orientation of the self is conveyed in flight. These differences are shown in Table 2.

Table 2. Natural orientation cues versus orientation cues available to pilots.

Natural Terrestrial Orientation Cues	Artificial and Natural Cues During Flight
Multisensory	Accurate orientation cues usually limited to vision
Appropriate distribution of sensory demands across channels/modalities	Visual overload, accompanied by under-utilization of other senses
Use of each sensory modality in its area of strength[6]	Use of vision for conveying information usually conveyed via other sensory modalities[7]
Ambient/immersive	Usually focal and with limited field of view
Intuitive	Often abstract/symbolic
Having concordant frames of reference	Having multiple frames of reference within and across senses • Frame of reference of display may not match ego frame of reference of user[8] • Out-the-window visual cue is Earth-referenced, general interior view (inside the cockpit) is not, and focal attitude indicator is. [9]

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[6] [16].

[7] [17].

[8] For example, using a head-mounted display showing right roll attitude while looking 90 degrees to the left could make the right roll be interpreted as forward pitch.

[9] Auditory and tactile/kinesthetic processing also suffers from multiple frames of reference.

Holistic/seamless	Usually requires cross-referencing several displays
Integrated	Artificial cues may disagree with vestibular/somatosensory cues
Nearly immediate	Delays in display update with head motion, aircraft reaction to control inputs, etc.
Usually short duration and frequency range of body motions within our normal experience	Motion outside the normal range we are evolved to perceive correctly
Background of constant 1G vertical force cue due to gravity	Higher and lower than normal G, causing change cues to “down.”
Mostly two-dimensional movement space (across surface of Earth)	Fully three-dimensional movement space
Close, active reafference (between control outputs vs. actual/expected afferent inputs)	Periods of passive conveyance (when not piloting the craft or when auto-pilot systems are engaged)

It should be obvious from a review of Table 2 why disorientation occurs frequently in flight but rarely during terrestrial locomotion. In fact, given the entirely inadequate (and often misleading) cues available in flight, it a wonder that aircraft do not crash more frequently than they do. There are many ways in which existing displays could be improved and new displays developed.

Of the three countermeasures for SD (selection, displays, and training), advanced displays offer the greatest promise for eliminating SD during manned, human-controlled flight. This will most likely be achieved by providing veridical information to the pilot in the same way it is provided during natural locomotion, viz., via a seamless and intuitive multisensory suite of cues [14];[15];[17]. Solving SD via better displays can be considered a very valuable approach, but one that is still being refined and transitioned for widespread use by aviators. Until that occurs, the most immediately ready and least expensive approach to SD prevention will be training, which is discussed next.

2.3 SD Training: Approaches Taken and Opportunities Lost

SD training is the most easily-implemented SD countermeasure. SD training is not necessarily the best means of eliminating SD in the long run, however, and it should be done carefully so that students do not think past SD victims are people who simply failed to listen adequately in class. Nevertheless, thorough training should be required for all pilots and should be updated and improved wherever feasible.[10] There are several approaches to SD training, with somewhat different goals (see Table 3). In general, the authors of this report favor phenomenological and flight-based training over lectures. Direct demonstrations of SD are recommended, along

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[10] Specific recommendations for training improvement are described later in this report.

with the opportunity to practice recognizing and recovering from SD during actual flight training. Such demonstration and training should be components of every pilot's education.

Table 3: Approaches to SD Training

	Ground-Based.	Flight-Based
Didactic	Classroom lecture	Informal pre/postflight coaching
Phenomenological	Experiential via demonstration devices	As part of a group demonstration flight
	Experiential via simulation training	As part of regular flight training

Bles (2008) pointed out that training lectures, demonstrations, and flight training procedures vary widely, and more careful assessment is needed concerning the outcomes of training. He provided a valuable overview of the SD training approaches among the NATO countries. It described fixed and rotary-wing classroom instruction, basic classroom demonstration of SD, demonstration on sophisticated ground-based SD devices and flight simulators, and in-flight training.[11] The U.S. military includes many of these components in their SD training [19]. Unfortunately, the excellent group inflight SD demonstration sortie [20] is not typically a part of U.S training anymore. Although the sorties added cost, they were certainly favourable in terms of benefits relative-to-costs [20], and afforded an excellent opportunity to experience SD situations first hand and under supervision from an SD expert. These sorties are still done in some of the U.K. military services, whose flight surgeons are qualified to fly these sorties in order to better induce and explain each SD illusion. These in-flight experiences give the student a direct experience of the flying conditions that can cause SD and give them initial instruction in avoiding such conditions or coping with SD once it occurs [21].

2.3.1 The state of expert recommendations concerning sd training

Over the decades, SD training papers have been written and expert working groups have been convened several times to formulate recommendations for improving SD training [20];[22];[7];[24];[25][18];[3];[26];[27];[28];[29];[30]. As far back as 20 years ago (in 1997), an SD training subgroup of the SD Tri-Service Working Group met several times at Pensacola Naval Air Station, to advise the military concerning areas for training improvement (see Appendix). The group included SD scientists, military physiologists, flight surgeons, and instructor pilots from the Navy, Air Force, Army, USMC, FAA, and NASA. Later, in 2000, under the direction of Dylan Schmorrow, Ph.D. (Navy Captain, retired) (and the sponsorship of the Office of Naval Research), another SD training workshop was held at Pensacola Naval Air Station [31]. Below are listed some of the more important recommendations for SD training improvement made by the aforementioned working groups and cited sources.

1. Initial SD training occurs early in the ground portion of flight training, but for greater effectiveness, it should be moved (or a refresher given) closer to later instrument training.

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[11] The Bles report is recommended for further reading, and the status of adoption of some of its key recommendations is discussed later in the current report.

2. Ground training should augment classroom lectures with direct demonstration and experience of SD, preferably using advanced SD demonstration devices allowing more sophisticated instruction than is possible with the Bárány chair (e.g., the Navy's Multi-Station Disorientation Demonstrator or MSDD).

3. The most effective method of demonstrating SD is in-flight, using a dedicated SD group sortie such as that employed by the U.K. military [20].

4. Individual flight training should include not only the demonstration of SD, but also effective recovery from SD.

5. Individual flight training should include not only recovery after being placed into an unusual attitude by the Instructor Pilot, but students should also be allowed to fly themselves into a state of SD and then recognize and recover from it.

6. Regular in-flight SD refresher training should be conducted.

7. SD is not limited to aerobatic flight or vigorous acceleration situations, so SD training should include some subtle disorientation effects (e.g., subthreshold drift during helicopter hover).

8. Inflight SD recovery training should include the presence of a distractor and/or a workload pressure.

9. SD training should be more standardized across the NATO countries and the military services within each country.

10. Formal, quantitative assessments of the SD training effectiveness should be made, via testing students on classroom material and tracking SD mishap rates as a function of SD training improvements.

11. One of the best means of determining whether a pilot is distracted from the primary flight instruments during instrument flight (and therefore likely to become disoriented very quickly) is to know his/her direction of gaze. Eye-tracking would be a useful adjunct to SD training and also to SD mishap evaluations.

12. SD training should emphasize case-based review and recreation of past mishaps, especially where the scenarios being discussed and demonstrated have commonly contributed to mishaps.

13. SD training and demonstrations should be extended beyond pilots, to include aircrew and associated personnel.

- Many of these recommendations have been repeated in multiple working groups and publications over the years, and some go back as far as 20 years. A few examples are provided below:

- Recommendations #1-4 above were mentioned in 1997 as part of the Spatial Disorientation Triservice Working group meeting (e.g., in the Training Initiatives lectures shown in Braithwaite et al., 1997 [22])

- Recommendations #1, 2, 3, 9, 10, and 12 were made in 1997 by the Spatial Disorientation Training subgroup of the Triservice Working Group (see Appendix).

- Recommendations # 2, 6, 9, and 12 were made 17 years ago in a Navy point paper by Schmorrow (2000).
- Finally, recommendations 9 and 12 were made by Estrada et al. in 2003.[12]

What do people familiar with U.S. Army training think about the current status of SD training in regard to these long-standing recommendations? A personal communication with a colleague [32] who is an Army flight surgeon and SD researcher led the first author of the present paper to infer that many of the 12 recommendations above have not yet been fully adopted by the U.S. Army. This inference was further corroborated by another colleague [33] who is an Instructor Pilot and Head of the Leadership Department at the U.S. Army Warrant Officer Career College.

How widespread is this problem? What about SD training outside the U.S.A.? Col Ian Curry, M.D., the second author of this report (a British flight surgeon, rated pilot, and SD researcher) confirms that these suboptimal training trends are not limited to the U.S. Army. This view is corroborated in the literature: Willem Bles [18] provided an excellent summary of training up to the year 2006 across 13 countries including Spain, Czechia (Czech Republic), Sweden, Greece, Italy, Germany, Austria, France, The Netherlands, the U.S.A., the U.K., Canada, and New Zealand. Of the 13 countries evaluated, all but 1 provided ground-based SD demonstrations beyond the simple Bárány Chair demonstration (Recommendation #2). Unfortunately, only 5 countries clearly provided a formal/structured program of inflight SD demonstrations (Recommendation #3), and only 1 evaluated training effectiveness in terms of reduced mishap rates (Recommendation #10). Therefore, it appears that as of 2006, two of the key training recommendations of SD experts had not been adopted widely across these countries. Is this still true now, more than a decade after the training data collected by Bles?

COL Gaydos (personal communication, 10 April 2017) made the first author aware of a more recent Air and Space Interoperability Council (ASIC) report on Spatial Disorientation, which provides additional information concerning the state of SD training in the branches of the U.S. military and in the military services of some U.S. allies. This publication (in Bles, 2008) summarizes the state of tri-Service SD training across its five member nations (Australia, Canada, New Zealand, United Kingdom, and the U.S.A.). These findings are summarized in Table 4, with the greatest detail preserved for the largest member country, the United States of America (for which the Air Force, Army, and Navy are broken down as USAF, USA, and USN, respectively). As can be seen in Table 4, the situation has not improved dramatically since the Bles 2008 report, and many important SD training recommendations made over the years still have not been adopted universally.

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[12] This publication alludes to recommendations going back much earlier as well.

Table 4. The Current State of SD Training Relative to Past Recommendations (Inferred from the 2016 Air and Space Interoperability Council Report

	United States of America			**Other ASIC Countries**			
Past Training Recommendations	U.S.A.F.	U.S.A.	U.S.N	Australia	Canada	New Zealand	United Kingdom
Lecture/demo late, near instrument training? (Recommendation 1, above)	No, still done early in training						
Advanced ground-based demo.? (Recommendation 2)	No, only Bárány mentioned in report[13]		Yes, Bárány + MSDD[14]	Yes, Bárány + Gyro1		No, only Bárány mentioned	Yes, Bárány + Gyro1
Dedicated in-flight demo. sortie? (Recommendation 3)	Structured training, but not dedicated sortie	No structured program mentioned					Yes, dedicated group sortie demo.
In-flight SD Training During Individual Flight Training? (Recommendation 4)	Yes	None mentioned[15]	Yes, partially, via recovery from unusual attitude but not necessarily flying oneself into SD				
Regular SD Refresher Training? (Recommendation 6)	Yes, lecture & simulator every 5 years	Yes, as often as annually in inflight refresher	Yes, lecture every 4 years	Yes, lecture every 3 years	Yes, lecture every 5 years		Yes, lecture every 4-5 years + demo. (Bárány or sortie)[16]
easurement of Training Effectiveness? (Recommendation 10)	None mentioned	(No answer provided)[17]	Yes, SD training + exam	No	(No answer provided)	Not re. mishaps, but some exam	Yes, training + survey mishap tracking

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[13] The Air Force has several devices and used to use the Advanced Spatial Disorientation Demonstrator during some of its training. The Air Force and Army have been known to send students to the MSDD for demonstration.

[14] In addition, visual illusions of SD have been trained in the past, using a ground-based part-task simulator.

[15] Note, however, that an Army Instructor Pilot confirmed that partial training via recovery from unusual attitude is done.

[16] Specifics vary by branch of service.

[17] It is known that mishaps due to various causes are studied fairly regularly and that an unpublished study by Estrada et al. (described by Gibb et al., 2011) was conducted, which concluded that various SD prevention efforts carried out between 2000-2005 had saved 12 aircraft, 20 aircrew, and $500M (which is more than $640M in 2017 dollars).

Summarizing the findings from the aforementioned personal communications and from the ASIC report, it appears that many of the SD training recommendations from the literature have not been adopted. For example, recovery after having been placed into an unusual attitude (by the instructor pilot) is usually practiced instead of being exposed to circumstances where one flies oneself into an unusual attitude. This essentially means that pilots are being trained to correct a known SD after instructor prompting rather than to identify and correct an unrecognized SD on their own and without prior warning. It would be beneficial if students were exposed artificially to an unexpected and intermittent loss of outside visual reference (forcing them to decide when to fly by instruments alone) under conditions of high workload and distraction. Such an inflight scenario would be highly relevant to SD mishap prevention training, in the view of 21 SD experts [34]. Wherever feasible, ground-based and inflight scenarios should be based on actual mishaps [25].

Given how many lives and aircraft are lost due to SD, it is dispiriting to learn that repeated, expert recommendations concerning SD training improvements (some going back 20 years) have still not been adopted throughout the services. In fact, the 2003 assertion by Estrada et al. that there was a "lack of creativity and innovation in regards to SD awareness training" (p. 24-4) seems a legitimate statement today as well.

SD training has improved in certain respects over the years, but why has it not improved faster? There are at least four reasons why SD training recommendations have not been adopted more readily and thereby saved more lives:

1. First, many of the recommendations for improving SD training incur greater cost in equipment and labour than continuing to train as before. Although the long term cost would be much lower even if only a few additional mishaps were avoided by better training [20];[3], the near-term constraints of each fiscal year tend to reign, thus slowing innovation.

2. Second, insufficient communication and coordination occurs between the SD experts and the SD trainers, leaving the training commands or agencies entirely responsible for improvements to the syllabus. This is partly because some training commands are not aware of the experts available to them. It is also partly because of researcher incentives, since scientists working actively in SD are beholden to their funding sponsors to meet research milestones, rather than to provide free advice to training commands, unless of course, their job is to do training research. It has often been recommended that a closer relation should be established between science and training (often called "training the trainers"), so that training commands can more easily fund needed consultation by scientists, and scientists can more readily forward collaborative training-relevant research proposals.

3. Third, it is likely that proper recognition of the direct and proximal way SD causes mishaps has been blurred by the confusing proliferation of overlapping mishap contributors and categories which have been named over the years, such as Loss of Situation Awareness, Controlled Flight Into Terrain, Approach and Landing Accidents, Loss of Control, and Degraded Visual Environments [35];[2]. This results in improper understanding of the critical role of SD in mishaps, confusion during mishap analysis/classification, and fads concerning incident and mishap terminology. Such a confusion of terms harms training.

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[18] However, the wrong agency is listed as monitoring mishap SD mishap rates, on page 24 of the 2016 ASIC report. The Naval Aerospace Medical Research Laboratory was disestablished by Base Realignment and Closure in 2010 and realigned to Wright-Patterson Air Force Base, to be replaced by the Naval Medical Research Unit Dayton.

4. Finally, it may be that improvements to SD countermeasures and training (and indeed, many other spheres of human activity) are not adopted via a focused and sustained push from the innovators, unless there is a concomitant pull from the people who will adopt and disseminate the innovation [36]. This process is a "two steps forward and one step back" affair. For example, the U.S. Army adopted the excellent U.K. group flight demonstration sortie for improving SD understanding in the early 2000s but no longer conducts the demonstrations today as part of their regular training. Interested parties come and go regularly, on both sides of the innovation and dissemination equation.

2.3.2 Comments Concerning the SD Phenomena Most Meriting Training Emphasis

In a detailed and excellent review of SD training, Bles (2008) discussed which SD phenomena were considered most important to demonstrate during ground-based training for fixed-wing and rotary-wing flight, according to the Aircrew Standardization and Coordination Committee (ASCC) Air Standard 61/117/14 (as summarized in Bles, 2008). Some phenomena were designated by the ASCC to be "essential" for pilots to understand (and if feasible, experience), while others were deemed merely to be a "desirable" part of training.[19] While the list of SD phenomena was fairly complete, the authors of the present report question the some of the ASCC's rankings of the relative importance of the phenomena. A consideration of the relative training importance of the Coriolis illusion versus the G-excess effect will illustrate where we feel a different ranking was needed. In fixed-wing flight, the Coriolis illusion (a false perception of head-and/or-self velocity associated with self-rotation plus head movement) is deemed an essential part of training. This is the case, despite the fact that the literature indicates that the low angular velocity and large radius of most banking turns in a fixed-wing aircraft are insufficient to induce severe Coriolis cross-coupling effects [37];[38]. In other words, the Coriolis effect is seldom a significant factor during standard manoeuvres in fixed-wing flight. Instead, the effects usually associated with Coriolis cross-coupling are mostly due to the G-excess effect. Nevertheless, the G-excess effect is deemed merely a "desirable" aspect of SD training. This seems like an improper emphasis that should be reconsidered in future meetings of the ASCC. Even when maximal Coriolis cross-coupling is produced in the lab under ideal conditions (via a large and rapid head movement made during high angular velocity on-centre body rotation), the disorientation sensation is still transient. Coriolis cross-coupling could occur during prolonged aileron rolls or while in a flat spin but only the latter situation would last long enough to have severely disorienting effects, and while there is no doubt that Coriolis cross-coupling can cause transient vertigo and loss of dynamic visual acuity (due to nystagmus), the most prominent and lasting effect of this stimulus is nausea (along with other symptoms of motion sickness, Lawson, 2014 [14]).

What about Coriolis cross-coupling during rotary-wing flight? Certainly, a helicopter is capable of rotating about its own axis rapidly or executing a banking turn about a very small radius compared to most fixed-wing aircraft. Nevertheless, most intended rotations of a helicopter about its own axis are not of sufficient duration (lab stimuli usually involve at least 30 s of prolonged constant velocity rotation) to cause severe disorientation due to Coriolis cross-coupling. Similarly, while tight banking turns in a helicopter may last longer than 30 s (e.g., due to repeated circling as part of a search), they do not usually involve a sufficient number of revolutions without interruption to trigger severe Coriolis cross-coupling (e.g., in typical laboratory studies, more than 10 complete revolutions are commonly executed, due to the need to accelerate to a constant velocity and then hold that velocity for a period of time prior to the head movement.

In summary, while Coriolis cross-coupling can occur in rotary wing flight and will tend to be more severe than it is in fixed-wing flight (with the exception of vigorous manoeuvres aerobatic craft or super-agile craft), as with fixed-wing flight, the vertigo it elicits will tend to be transient and mild. Moreover, it should be noted that a

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[19] Bles (2008) summarizes training events in these two training priority categories in Section 6.3.1.1 of his report.

greater tendency for Coriolis cross-coupling during rotary-wing versus fixed-wing flight does not imply that Coriolis effects are more important during flight operations than G-excess effects when a pilot is engaging in rotatory-wing flight. Evidence of the G-excess effect has been detected at 1.3Gz in a preliminary study [39], so G-excess is likely to be present during many helicopter manoeuvres. A conservative approach to rotary wing training would be to ensure that both types of perceptual **phenomena** are taught. It is likely that the Coriolis illusion is emphasized merely because it is easier to demonstrate on the ground. Nevertheless, if only one of these two phenomena could be taught to aviators, it should be the G-excess effect. This is why the authors recommend that Coriolis cross-coupling be considered as merely "desirable" during SD training. This and other points where the ASCC Air Standard 61/117/14 could be modified are shown in Table 5.

Table 5. SD phenomena which could be reconsidered in terms of how essential they are to treat thoroughly during flight training

SD Phenomenon	Current Classification	Recommended Classification
Somatogravic illusion	Desirable	Essential
G-excess effect		
Coriolis effect	Essential	Desirable
Oculogyral illusion		

2.3.3 Further Considerations for SD Trainers: Nine Common Myths

There are several incorrect points routinely made about SD in the training context and even sometimes in the literature. It is important for SD educators to be aware of these errors so they do not foster incorrect understanding among their students. To assist with correct understanding, we provide a list of nine common myths about SD, below. Myths #7-9 below are general points that are also pertinent to crew resource management and were originally framed in that context by Salas et al. (2002).

Myth 1: SD is the same as vertigo, or a conscious feeling of one's "gyros being tumbled."

> This conscious sensation can happen, but as was discussed in this report, most of the time, SD is subtle and happens without conscious awareness.

Myth 2: Pilots should train to know the symptoms of SD so they recognize SD before it happens.

> This myth is partially true. While pilots should experience recognized SD during training demonstrations and in flight, they should know that unrecognized SD is the most common type of SD and it has no particular symptoms. This is why it is important for pilots to become aware of the flight situations and stimuli that are most likely to cause SD. They do this by being exposed to the most common situations by an instructor, and by learning about situations which have led to past SD mishaps.

Myth 3: DVE, brownout, and controlled flight into terrain directly cause mishaps.

> It is important to distinguish contribution versus cause versus outcome: DVE or brownout are among the multiple contributors to SD and LSA. SD or LSA then directly causes inappropriate control inputs. These

bad inputs then lead directly to deadly outcomes (not contributors), such as controlled flight into terrain.

DVE or brownout describe an environmental circumstance that robs a pilot of reliable outside visual cues. This situation contributes to SD (and then to bad control inputs) if the pilot is not able to attend and respond efficiently to visual cues from his/her instruments. Lacking outside or instrument cues, the pilot must rely solely upon vestibular and somatosensory cues. When these nonvisual cues are not veridical (such as when one is drifting in hover below the threshold of detection of movement or in a banked turn or climb that creates centrifugal force), the pilot will fail to understand his true position and motion relative to the terrain, which is SD. The pilot then will make inappropriate decisions and inputs.

The inappropriate reactions of the pilot are not merely due to absence of visual cues, but rather, occur because multiple sensory systems provide information that is consistent with a nonveridical inference about one's orientation and motion. Even in the case of the vection illusion (an illusion of self-motion usually triggered by a moving visual field, such as that created by helicopter rotor wash during DVE), the illusion is triggered most readily when the visual interpretation is most consistent with visually-concordant but similarly nonveridical inputs from other sensory systems. It is the coherent visual-somatosensory-vestibular illusion which allows SD to occur, by fostering a highly compelling but non-veridical mental model of the environment surrounding the pilot. Just as healthy but blind people do not run into objects or fall over unless they have an incorrect mental model of the physical environment, so pilots manually in control of aircraft do not crash unless the total sensory-cognitive situation renders their understanding of the environment incorrect.

DVE and brownout are predicating conditions which make a mishap more likely, but the mishap only occurs if the pilot also becomes disoriented and therefore supplies erroneous control input to the aircraft. Conversely, controlled flight into terrain is not a cause of mishaps but an effect of SD leading to a category of mishap known as CFIT.

Myth 4: SD is mainly caused only by vigorous flight manoeuvres ("yanking and banking.").

While large G forces can contribute to profound SD, SD does not require high-G manoeuvres and in fact, can occur during subthreshold body motion (such as slow undetected drift while trying to hover a helicopter). SD can occur readily in less agile aircraft. Any commercial jet passenger has experienced SD. We have all perceived the cabin interior to be upright, but then have looked out the window and been surprised to see the plane in a banking turn. This occurs because, in the absence of veridical Earth-referenced information (which is absent when viewing the interior of the cabin), the passenger's interpretation of "upright" must be derived from the resultant between the gravitational and centrifugal force on his/her body.

Myth 5: Spatial orientation is 80% visual.

It would be accurate to say that manned control of aircraft has been designed in such a way that, when flight causes inaccurate somatosensory or vestibular inputs, accurate spatial orientation must be maintained visually. However, the myth that spatial orientation is 80% visual is often expressed as a specific and quantitatively verified principle of human orientation functioning, rather than a qualitative generalization that applies loosely to manned flight. Under most circumstances, spatial orientation is not 80% visual.

This myth most likely derives from a 1957 assertion by Fixot that half of the brain was devoted to vision anatomically and two-thirds of brain activity was involved with visual processing. These general neurological observations cannot be extended directly to spatial orientation functioning for several reasons.

First, the assertion concerned gross anatomy and physiology, rather than being an empirically-derived statement specific to an individual's ability to understand their own orientation. The observation that in general visual processing makes heavy demands on the brain is true, but this fact does not logically require the conclusion that a specific multisensory function (the maintenance of orientation) is mostly visual. The visual brain must process many types of information that are not always directly related to spatial appreciation of one's moment-by-moment physical orientation versus the environment (such as object colour, human language, quantitative graphs, facial expressions, object recognition cues, or edge detection cues). Moreover, each of these subtypes of visual information is incredibly processing-intensive compared to information from other senses. Many layers of brain processing are necessary to build a coherent mental visual scene of the environment in one's field of view. The problem can be understood intuitively and metaphorically by non-specialists by considering the average size of a file needed to convey 1 minute of music (~1-2 MB) compared to the average size of a file required to convey 1-minute of video (~300-700MB). The analogy to human vision and audition is imperfect, but it does illustrate the extraordinary amount of information contained within a moving visual scene. Regardless, the fact that visual information is more difficult to process does not imply that it is more important (than other sensory information) to spatial orientation. The maintenance of normal spatial orientation is by no means mostly visual. In fact, the visual system is too slow to maintain good visual acuity during rapid head movements. Rather, spatial orientation is maintained mostly by tactile, kinaesthetic, visual, and auditory inputs working in concert and calibrated with one another mainly by the vestibular system.

Myth 6: SD mishaps can be eliminated with high quality training.

SD can only be reduced by training. SD during manned, controlled flight is essentially a human factors problem that will only be solved by designing aircraft displays that prevent SD from occurring.[20]

Myths 7 and 8 are listed together because they represent two sides of the same misconception about training:

Myth 7: Pilots who have experienced SD training are ready to design and conduct SD training

Myth 8: Only SD experts should determine the design of SD training.

The truth lies between these two extremes. Pilots have task domain knowledge to enable them to evaluate the relevancy of training to their job. However, scientific experts on SD (and on training in general) understand the principles of perception and learning and are able to evaluate the scientific accuracy of the training material and its relevance to proven mishap contributors. Therefore, effective training program development must involve a collaborative effort between SMEs and learning experts.

Myth 9: Positive ratings of training are proof that learning has occurred, and on-the-job behaviour will improve.

To keep trainees alert and attentive, it is important that they feel engaged in the training. However, positive ratings are not sufficient: it is also necessary to test trainees concerning their comprehension and to evaluate whether training has improved team performance and decreased SD incidents and mishaps. Simply evaluating the trainee in the artificial training environment to see if the trainee met training objectives is not enough. It is necessary to evaluate transfer of training to the job setting.

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[20] It could also be eliminated via fully reliable systems that take over aircraft control when needed.

2.3.4 Further Considerations for SD Trainers: General Educational Principles to Follow

We have attempted to dispel some common myths that should not be proliferated during SD training. Next, we will widen our discussion to briefly convey some general principles of any good training program [42]. As SD training is improved further in the coming years, it is hoped that many of these principles can be incorporated or strengthened.

A good training program typically follows six steps:

1. Identify training needs
2. Establish training objectives
3. Develop instructional materials
4. Test and refine materials
5. Implement training program
6. Evaluate training program

These steps are all important when designing, or redesigning a training program. However, individual steps are often overlooked or not followed through completely, resulting in a less-than-optimal training program. For example, training programs often overlook the need to implement a consistent training program across trainers and standardize it for the aspects of training that are not platform specific (Step 4). Similarly, the advantages of evaluating the efficacy of training (Step 6) are sometimes often overlooked during SD training.

When identifying training needs comprehensively, results from three perspectives are typically examined: organizational analysis; task analysis and person analysis. The organizational analysis takes a broad look at the role of training in the organization. For SD training, the organizational analysis would look at SD related mishaps organization wide. A cost analysis for SD mishaps might be performed. Training then might target the most common or most costly SD events. A task analysis focuses on what the trainee must do to perform correctly to avoid and recover from SD. For SD training, a task analysis could focus broadly on recognizing SD or specifically on how to recover from a specific case of SD. A person analysis examines the qualifications and skills of the trainee to examine what the trainee brings with them to the job and what must be trained to fill the lack of skills. A person analysis could also be performed on the trainers to make sure that the trainers are ideally suited to perform the training.

When establishing training objectives, it is important to establish observable and measurable objectives. For example, from an organizational perspective a training objective might be to decrease SD related mishaps by 25%. From a person perspective, training objectives must be equally measurable, e.g., a 25% improvement in a trainee's ability to identify circumstances that may lead to SD. Making the training objectives measurable helps to provide appropriate training feedback to help people learn, and permits analysis of aspects of training that are working or not.

Different instructional materials are required for different training situations. It is always important to keep in mind the measurable training objectives when identifying training materials. Transfer of training metrics can be built into a training program to provide data on whether new training materials have increased or decreased the effectiveness of the training. Consideration must be given to the recency of the materials, i.e. whether the materials should be updated.

No training course is complete without an iterative process that involves testing and refining the materials. Course feedback surveys can be given to the trainees immediately following the course and then later after they have performed the job. This gives feedback to the instructors from subject matter experts and offers insights into what was and was not effective about the training and the materials used. Testing and refining should occur at the beginning of a new course, the insertion of new course materials, and regularly during the life of a course.

In the final step, the training program is evaluated for effectiveness. In terms of SD training, evaluation is probably most important at an organizational level. In other words, did the training reduce SD related mishaps? This step is often overlooked because of the difficulty in relating the organization wide data to localized training programs. This is why it is so important to strive for standardization in SD training and design and implementation of the training programs at an organizational level.

3.0 CONCLUSIONS

Spatial Disorientation (SD) is a major contributor to mishaps among aircraft that are manned and pilot-controlled. The main SD countermeasures over the years have been personnel selection, orienting displays, and SD training. SD training is worthwhile but it alone cannot eliminate SD mishaps. SD classroom training is in need of updating and greater standardization, while many improvements are needed to ground and in-flight SD demonstration training. Some degree of standardization of classroom training has been attempted where appropriate, with various NATO standardization agreements (STANAGs), Aircrew Standardization (ASCC) meetings, and an excellent USAF website in the early 2000s. Nevertheless, there has been a general lack of continuity and sustainment.

Specific expert recommendations for improvement have been made in each of these SD training domains for more 20 years, but widespread adoption of the recommendations has not been forthcoming. For example, Gibb et al. lamented in 2011 that the Air Force had been requesting a new ground-based SD trainer for 30 years. The Air Force had experimented with the Advanced Spatial Disorientation Simulator in the 1990s, but this does not appear to have been adopted system-wide. The Navy has just completed a new Disorientation Research Device (nicknamed The Kraken) at the Captain Ashton Graybiel Acceleration Research Facility at the Naval Medical Research Unit in Dayton, but it has employed the useful Multi-Station Disorientation Demonstrator for ground-based SD training for ~35 years. The Army had an excellent in-flight SD demonstration program based on the U.K. program, but that has not been continued. It appears that eliminating deaths due to SD will await the tri-Service dissemination of automated ground-collision avoidance technologies, which themselves took more than 20 years to be accepted.

Training alone is not a definitive solution to the SD problem, but it is a readily-applied countermeasure. More vigorous and better coordinated efforts to improve SD training over the last few decades may have saved additional lives. Sadly, missed opportunities for SD training improvement have been lamented before, over the last decade, by Braithwaite et al. (2004), Cheung (2013), Gibb et al. (2011), and others. These lost opportunities are not the fault of the dedicated instructor pilots, who strive for excellence within the constraints of their funds, equipment, time, syllabus requirements, and knowledge. Rather, closer coordination between research and training commands or agencies is needed.

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