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Near-Future Technological Countermeasures for Spatial Disorientation in Flight

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Spatial Disorientation (SD) is an important cause of deadly aircraft mishaps, despite improvements in night vision, head-up-displays, cockpit automation, etc. This paper explores several technological countermeasures for SD. This report begins by discussing the magnitude of the SD problem and the reasons why technological countermeasures are needed. The authors discuss the three main approaches that are typically used (improved selection, training, or technology) to decrease the incidence of SD, and argue that improved selection and training, although beneficial, are not sufficient by themselves to prevent SD. The authors introduce various technological solutions they are developing, including better models to predict disorientation, as well as better cockpit displays to provide accurate earth-referenced visual, auditory, or tactile cues. The authors describe how these technological approaches should benefit situational awareness, spatial localization, detection of sub-threshold vehicle motion, and prevent imminent collision with objects that are not being attended to by the pilot.

Aviation spatial disorientation (SD) is best described as a pilot's inability to correctly interpret aircraft attitude, altitude, or airspeed in relation to the earth (Benson, 2006). It is well known that SD in manned aviation can contribute to various accidents and even the loss of aircraft. Moreover, SD is the number one cause of Class A mishaps. These are incidents where the total cost of damage is $1 million or more and/or the aircraft is destroyed and/or fatal injury and/or a permanent total disability has occurred. Spatial disorientation and the loss of situation awareness (SA) also occur in unmanned aviation, even with operators on the ground. Interestingly, losses of aircraft and equipment in manned aviation over the last decade are very low in comparison to unmanned aviation where losses are high and increasing (Zirkelbach, 2007). McCauley & Matsangas (2004) showed that maintaining SA is also a key factor when operating unmanned aerial vehicles (UAVs). Although this paper is not specifically about UAVs, it is important to keep in mind that UAV operators and pilots of manned aircraft face similar challenges when it comes to maintaining SA. Three primary approaches (training, improved selection, and technology) have been used to decrease the incidence of SD. Although training and improved selection can be beneficial, they are not sufficient in and of themselves to effectively prevent SD. Technological solutions, in conjunction with effective training and selection, may provide a better means of enhancing and maintaining SA and, thus, preventing SD.

Regardless of a pilot's experience or expertise, sensory illusions can lead to perceived discrepancies between instrument indications and what the pilot feels the aircraft is doing (Zirkelbach, 2007). The subsequent mishaps are not only costly to the military, but often result in the loss of human life. For example, between 1993 and 2013, the United States Air Force (USAF) experienced 72 SD related Class A mishaps resulting in a loss of 65 aircraft for a total cost of $2.32 billion and even more important and unfortunate, the loss of 101 lives (Poisson, 2014). These consequences of SD are enormous, in the cost of lost aircraft, lost aircrew, and the cost of training new aircrew (Heinle & Ercoline, 2003; Zirkelbach, 2007). Additionally, between 1992 and 2000, SD caused 20.2% of USAF Class A mishaps. During an equivalent period, SD caused 27% of U.S. Army mishaps and 26% of U.S. Navy (USN) mishaps. In general, SD is still the most common cause of human-related aircraft accidents (Heinle & Ercoline, 2003).

Selection as a Countermeasure

Aviation, both manned and unmanned, provides numerous advantages, not just for transportation and combat, but also for intelligence collection, surveying and monitoring, etc. However, the technological complexity of cockpit designs and UAV controls, combined with stressful situations, adverse weather, and other workload drivers can cause problems for aircrew and may increase the likelihood of pilots becoming spatially disoriented. Thus, selecting the best individuals for the task is incredibly important.

Numerous pilot selection methods have been utilized since the beginning of manned flight. General screening procedures have included age, physical condition, and general intelligence. In the U. S. military, paper-and-pencil perceptual-motor and cognitive tests have served as traditional selection tools (common examples include: the Aircrew Classification Battery, the Wonderlic Personnel Test, Spatial Apperception Test, Academic Qualification Tests, Mechanical Comprehension Tests, etc.).

Traditionally, perceptual/cognitive selection test batteries consist of at least four components: 1) a general intelligence tests that has both quantitative and verbal items, 2) a spatial test (e.g. the Spatial Apperception Test), 3) a mechanical comprehension test, and 4) a background/biographical inventory. The Aviation Selection Test Battery (ASTB), used by the USN, was first created in 1942 but has since gone through a few revisions (Williams, Albert, & Blower, 1999). The 1992 version of the ASTB has six subtests: the mechanical comprehension test, the math-verbal test, the spatial apperception test (which measures spatial reasoning abilities), the aviation and nautical information test, the biographical inventory (which contains personal history and general interests questions), and the aviation interest test (Williams, Albert, & Blower, 1999).

The six ASTB subtests are weighted and combined in order to calculate three validated scores utilized in pilot selection. The Pilot Flight Aptitude Rating (PFAR) is a validated predictor of flight grades during primary flight training; the Academic Qualification Rating (AQR) is a validated predictor of academic performance during ground school; and, finally, the Pilot Biographical Inventory (PBI) is a validated predictor of attrition during primary flight training (Williams, Albert, & Blower, 1999). Data provided by the Naval Operational Medicine Institute (NOMI[1]), the organization responsible for overseeing the ASTB testing program, indicates that approximately half of the individuals who take the ASTB do not meet the minimum naval aviation selection scores (Williams, Albert, & Blower, 1999). Ultimately, after the additional steps in the selection process (e.g. physical examination, interview, board evaluation), only 15% are selected to begin training (Williams, Albert, & Blower, 1999).

Although the ASTB has been shown to be a useful and valid selection tool, it is not without its own shortcomings; namely, it and other paper and pencil tests fail to reflect the dynamic cockpit environment inside military aircraft. As a result, the Navy recently developed a Performance-Based Measurement Battery (PBMB) as a supplement to the ASTB. The PBMB is administered online through the Automatic Pilot Examination (APEX) system, which affords opportunities for more dynamic assessments. The last three of the seven subtests involve multi-tasking and/or emergency procedures scenario. These multi-tasking elements and the emergency procedures scenario are aimed at assessing dynamic skills that pilots need to effectively operate military aircraft. For example, Ostoin (2007) found that the PBMB detected important hand-eye coordinated tracking skills, something that the paper and pencil ASTB cannot assess.

It is important to note that although selection tools are helpful in general, there is currently no selection tool specifically designed to assess aviators who are particularly sensitive to SD. While all aviators with functioning vestibular organs can be made disoriented, some healthy aviators will be more

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[1] On 26 October 2011, NOMI was realigned directly under Navy Medicine Support Command (NMSC) and changed its name to Navy Medicine Operational Training Center (NMOTC).

susceptible to SD than others. Moreover, some aviators who appear healthy actually may have latent vestibular pathologies rendering them much more susceptible to SD than a normal person. These gap areas need further investigation. Despite the many current unknowns in selection, selecting pilots who are best suited to handle the complexities and challenges of aviation is very important. In general, selection is helpful in identifying intelligent and resilient individuals with the "strongest foundations" on which to build. However, those ultimately selected to become experienced aviators, are not immune from losing their SA and becoming spatially disoriented. Relatedly, Matthews, Previc, and Bunting (2003) found that pilot experience was a strong predictor of reporting SD incidents. Not only were more experienced pilots more likely to have more opportunities to experience SD, but they also reported a higher frequency of each SD illusion, independent of the total number of sorties flown (Matthews et al, 2003). They suggested that experienced pilots are better able to recognize specific types of SD compared to less experienced pilots. It may also be the case that more seasoned and confident pilots are more willing to report their SD experiences, knowing that it happens to virtually all pilots. Nevertheless, increased experience, or expertise, did not translate to a reduction in SD incidence. Therefore, one must examine other approaches to decreasing the incidence of SD, like training.

Training as a Countermeasure

The U.S. Army, USAF, and USN customarily have four primary components to their SD training curricula: some initial classroom-based training, ground-based demonstrations and/or simulations of SD, flight-based demonstrations, and finally, some type of refresher course or brief (Guckenberger & Bryan, 2003). Due to high costs and time constraints the tri-services have all cut back, if not eliminated entirely, flight-based SD demonstrations.

The classroom and refresher components not only provide general overviews of the problems and dangers of SD and the importance of maintaining proper orientation, but they also focus on educating the students on topics such as the orientation-specific aspects of the visual, vestibular, and proprioceptive systems, as well as the psychological aspects of orientation. Ground-based demonstrations are important training tools because they afford the opportunity to let individuals experience how their own senses can be fooled in some of the disorientation situations. Typically, Bárány chairs, and other disorientation devices, are used to elicit various disorientation illusions. Additionally, these types of demonstrations are useful in that they are (relatively) low cost and safe from the hazards of actual flight.

Although more costly and perhaps more hazardous, in-flight demonstrations afford the opportunity to experience SD situations first hand. Flight surgeons typically fly these sorties in order to better explain and point out the various facets of SD. Moreover, these sorties are flown so that students can experience SD for themselves, but with the safeguard of having an instructor pilot (IP) aboard. These in-flight training experiences are important because they allow for the IP to teach about flying conditions that can lead to SD situations. Moreover, these flights also afford the teaching of mechanisms that can be used to cope with the illusions after they have occurred (Braithwaite, Hudgens, Estrada, & Alvarez, 1998).

Although training has been shown to be beneficial in enabling pilots to identify SD situations, it is limited by the fact that the training is often aircraft-type specific. Although some generic training is possible, it is most effective when it addresses specific aircraft and their respective designs, specific operational scenarios and specific environmental situations. For example, Williams and colleagues (2014) demonstrated that spatial strategies training can help pilots avoid low nighttime approaches, thus "combating" the black hole illusion. After the training, pilots were able to perform nighttime approaches similar to those performed during the daytime with a visible horizon. In short, this training was very successful, but it was also very specific and does not necessarily extend to other spatially disorienting situations/illusions.

Similarly, skills obtained from generic training do not necessarily translate well to other, more specific aircraft. For example, the USAF Undergraduate Pilot Training (UPT) has a generalized flight training component. Although beneficial in establishing a good foundation and starting point for pilots, one of the major shortcomings of the UPT generalized flight training was that it failed to provide student pilots with knowledge and specialized skills that they would need in order to smoothly transition to the tanker and large transport aircraft that account for one third of the USAF fleet (Weeks, Zelenski, & Carretta, 1996).

Research over the last few decades has demonstrated that SD training is effective, albeit often limited to specific aircrafts and/or specific situations and illusions. The tri-services' training curricula are very beneficial in educating students pilots about the dangers of SD—they also provide important learning opportunities for student pilots prior to actually flying their own aircraft. Selection, training, and experience are beneficial in helping pilots avoid losing their SA, but they are not foolproof. Arguably, they are necessary but not sufficient tools to combat SD. The addition of technological countermeasures may provide the key to bridging the gap, so to speak, and may provide pilots with another tool to better maintain their SA and avoid becoming spatially disoriented.

Technology as a Countermeasure

Under degraded visual conditions and especially if one is suffering from SD, pilots are taught to transition to instruments in order to discern their aircraft's true attitude. The head-down displays (HDDs; e.g. the attitude indicator, altimeter, heading and airspeed indicators), which have become standard in aircraft cockpits, are arranged in a "T" formation to facilitate a quick scan and determination of the aircraft's attitude (Albery, 2007). Numerous research studies over the last few decades have examined different display designs, layouts, configurations, etc. in order to improve the pilot's ability to determine the aircraft's true attitude and subsequently maintain SA. Although these instruments can be helpful, they do not eliminate SD. More recently, research has focused on alternative technological countermeasures that may be more successful at combating SD.

For example, Poisson (2014) examined the efficacy of an Attitude Stabilization Display (ASD), which differs from the standard attitude indicator by providing an auditory alert when the aircraft enters an unexpected attitude; the display is equipped with a "more intuitive graphical interface" and the ASD provides a very specific recommendation of a course of action to maneuver out of the unexpected attitude and return the aircraft to upright, wings level flight (Poisson, 2014). Although Poisson found mixed results when comparing the ASD to the traditional attitude indicator, he notes that the intent behind the ASD was to aid the pilot during spatially disorienting situations by alerting the pilot and drawing his or her attention toward the aircraft's instruments. Additionally, he stresses the importance that symbology and alerting systems, whatever type they may be, ought to be designed in a way that affords "quick and accurate recovery" from unexpected attitudes. Although eliminating SD may not be possible for any single instrument or device, multisensory technologies may provide pilots with the widest array of tools to help maintain SA and avoid SD.

Cockpits are loaded with display systems, dials, and meters, which inundate pilots with visual information. Traditionally, pilots have also been tasked with processing and making sense of this plethora of visual information. More recently, research has shifted toward designing more intuitive cockpit display systems, like the ASD, in order to minimize pilot workload. Additionally, multisensory technologies, like tactile and audiotactile cueing systems, have been developed in order to provide pilots with feedback that is not exclusively visual.

In degraded visual environments and under high workload conditions, the Tactile Situation Awareness System (TSAS) has been found to improve pilot performance (McGrath et al., 2004). Pilots flying the UH-60 Black Hawk simulator were able to use the tactile cues provided by the TSAS as a secondary source of sub-threshold drift information while operating under degraded visuals and in environments prone to SD illusions (e.g. height-depth perception illusion). The TSAS allowed pilots to better concentrate on mission tasks, thus resulting in increased SA and reduced workload (McGrath et al., 2004).

Audio feedback is another type of sensory cue that pilots could use to improve their SA; however, 3-dimensional (3D) audio cues are prone to fore-aft reversals and other localization errors, whereas fore-aft localization errors do not occur with vibrotaction. One consequence of multimodal integration, i.e. concurrent auditory and visual events, is that stimuli in one modality can influence our perception of stimuli in the other (Spence & Driver, 2000). For example, the ventriloquism effect refers to perceiving auditory sounds as coming from the same direction as the visually observed object, person, etc. As Spence and Driver (2000) point out, this effect is not limited to speech and lip-movements; it can occur for any concurrent visual and auditory cues. When examining crossmodal attentional issues, numerous studies have found that visual events "never" attract auditory attention (Spence & Driver, 2000). However, Spence and Driver found an exception to this rule, namely that spatial attention can, in fact, be drawn to the illusory location of a ventriloquized sound. In other words, visual events can attract auditory attention when paired with a concurrent unlocalizable sound. Furthermore, they found that ventriloquism, even for task-irrelevant stimuli, can happen swiftly and automatically with direct consequences for objective performance.

Importantly, this effect was only found with concurrent unlocalizable sounds; when the visual cues were paired with easily-localizable sounds, no effect was observed. Because 3D audio cues are subject to localization errors, pilots may fall victim to this effect and their attention may be inappropriately drawn to irrelevant stimuli. However, combining audio and tactile feedback may provide a means of avoiding the ventriloquism effect. The additional modality information presented by the combined audiotactile cues may equip pilots with better tools to combat the disorienting nature of degraded visual environments and high workload conditions. Audiotactile cues may be better at providing targeted, localizable cues to help pilots maintain SA.

Similarly, improving vibrotactile cueing displays may enable pilots' ability to more accurately perceive aircraft motion and/or approaching obstacles during flight. For example, Amemiya, Hirota, and Ikei (2013) found that by varying the speed of front-to-back tactile array stimuli subjects would increase or decrease their estimates of their illusory vection. Tactile arrays may also be used to convey approaching obstacles. Varying the rate and location of the tactile cues may be an effective means of conveying distance from an approaching object. Ultimately, effectively synthesizing the various types of information vibrotactile cues can provide could be very beneficial in helping pilots maintain SA.

Multisensory technologies may provide pilots with the widest array of tools to help maintain SA and avoid becoming spatially disoriented. One may argue that no single technological countermeasure may be effective at eliminating SD entirely; however, if all technological countermeasures were to effectively provide pilots with quick and accurate feedback to help maintain SA, then perhaps, in combination, they might be able to eliminate SD or at the very least, drastically minimize the likelihood of its occurrence.

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