Multisensory Integration for Pilot Spatial Orientation

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Last, but certainly not least, we are indebted to the many volunteer subjects for our three experiments. We would gratefully name them all, except that we promised them anonymity as a condition of participating in our experiments (per standard protocol). Their enthusiastic participation ensured that our experiments significantly contributed to the research literature.

Executive Summary

This report describes a 28-month Phase II SBIR project that modeled pilot spatial disorientation (SD) illusions as part of a real-time illusion detection and aiding system. The models and detection algorithms focus on human vestibular responses to aircraft motions. The detection subsystem purposely excludes orientation cues from other senses (e.g., vision) because contributions from those senses have not been quantified. Detection relies upon computational models of four illusions that are flight hazards: leans, graveyard spiral (both are somatogyral illusions), somatogravic, and Coriolis.

The aiding portion of the product is part of a comprehensive approach to combating the adverse effects of SD on military and civilian pilots. A comprehensive approach includes: pilot selection and training (which has shown recent successes); mission pre-briefings that emphasize SD susceptibility (e.g., when flying at night over featureless terrain); hypothetical intelligent cockpit aids that help pilots retain orientation and aid recovery when they are disoriented; post-mission analyses of flight data; and, a method for feeding back lessons learned from each approach component to the others. The components of focus for this project were the cockpit aid (which uses detection and aiding) and the post-flight analyses (where detection is key).

In the aiding subsystem, the multisensory countermeasures hypothesized cues and commands in the following modalities: visual, auditory, tactile, and olfactory. In the interest of completeness, we also hypothesized how an intelligent (context sensitive) aiding system could trigger auto-recovery (e.g., auto-GCAS) and auto-ejection (as a last resort to save the pilot's life, if the aircraft is damaged and unable to recover). The countermeasures were triggered based on three criteria: The detection portion's assessment of level of certainty that an SD event is occurring, the aircraft state, and the pilot's multisensory workload. For aircraft state, the main considerations are assessments of unusual attitudes and time to ground impact. For pilot workload, aiding suppresses countermeasures in modalities in which the pilot workload is high. For example, during radio chatter, audio countermeasures are suppressed in favor of visual and tactile ones.

Four experiments supported the detection and aiding calculations. Two focused on creating vestibular illusions and quantifying pilot perception of those illusions for our models. Data from the experiments were used in the models and included the exponential decay time constant for sustained rotations, and the magnitude of illusory rotation after halting a sustained rotation. Two experiments focused on the aiding portion of the system and tested an innovative visual cue, called the SD Icon, as well as the efficacy of voice and tactile commands for recovering from unusual attitudes. For three of the experiments, we drafted and submitted journal manuscripts.

The vestibular models formed the foundation of a tool for *post hoc* flight data analyses from SD mishaps. We analyzed mishap data from nine Air Force mishaps (some fatal), one fatal Navy mishap, and two fatal civilian accidents. The analyses were invaluable in fine-tuning the tool and our analysis process.

Other accomplishments include a patent application, professional conference presentations, a usability evaluation of our software product, and a preliminary examination of how to apply our results to the huge medical problem of elderly person imbalances and falls.

Recommendations for future work are to:

- Conduct more experiments, specifically to quantify visual dominance, and to test our aiding system in actual flight;
- Analyze more mishaps because the more data we analyze, the more we learn and the better are our models;
- Assist an accident investigation organization (e.g., Air Force Safety Center, National Transportation Safety Board) with ongoing accident investigations where SD is suspected;
- Analyze combat maneuvering data (e.g., from Red Flag exercises) to find, and adjust for, false positives;
- Apply our detection and aiding tools to UAV applications; and,
- Apply our detection and aiding tools to other domains – astronauts, divers, firefighters, and gerontology (since falls by elderly people are a huge medical expense in the US and elsewhere).

Readers interested in further details, or in pursuing these recommendations or others of interest to them, should contact the first author via phone (303.442.6947 x165) or via email at rsmall@alionscience.com.

1 Introduction

Spatial disorientation (SD[1]) continues to be an enduring problem in aviation. For example, during the 1980s and 90s, SD was a factor in approximately 21% of all US Air Force *Class A*[2] mishaps. Between October 1993 and September 2002, there were 25 high-performance fighter or attack mishaps where SD was identified as a causal or contributing factor. These mishaps resulted in 19 fatalities and cost the Air Force over $455 million (Sundstrom, 2004). In the United Kingdom, SD mishap frequency is estimated to be between 6 and 21%, depending on branch of service (Holmes et al., 2003). Furthermore, SD accidents are often fatal; in civilian aviation, Wiegmann et al. (2004) observed that over 90% of SD accidents resulted in fatalities.

Spatial disorientation, simply referred to as "vertigo" until becoming the subject of scientific research, is a normal response to neuro-physiologically confusing stimuli in the flight environment. The human body developed over eons to perceive motion on land in relation to the surface of the earth. In flight, however, these physiological systems can give the brain erroneous orientation information, resulting in SD. Most pilots will eventually experience SD; some pilots will experience it more acutely than others. In military aviation, attention mismanagement is a major contributing factor. In civilian flying (general aviation), accidentally straying into degraded visual conditions (e.g., flying into clouds) is the major contributing factor in this domain (Nall, 1999).

For this research, we use the definition of SD from Previc and Ercoline, who quote Benson: "SD refers to the pilot's 'failure to sense correctly the position, motion or attitude of his aircraft or of him/herself within the fixed coordinate system provided by the surface of the earth and the gravitational vertical.'" (Benson quoted in Previc & Ercoline, 2004, pg 1). This definition focuses on the issue of "which way is up?" while ignoring geographical orientation, "where am I?" The former is also our emphasis, with a further focus on the vestibular perception of which way is up (pitch and roll perception), and which way is forward along the desired path (yaw axis/heading perception). Even though a human's vision is dominant in determining spatial orientation, we ignore it within our models because there is no way that we know of (or presented in the literature) to quantify such visual dominance. Quantifying visual dominance is an area ripe for further research, as suggested in Chapter 4.

Our research is part of a comprehensive approach to the SD problem that includes: pilot selection (potentially), pilot training (which has shown promise over recent years already), mission pre-briefings (that emphasize SD susceptibility; e.g., when flying at night over featureless desert or the ocean), intelligent cockpit aiding systems (such as our SOAS), and rigorous post-event analyses (such as can be done with SDAT). The results of rigorous analyses feed back into the other means of combating SD to ensure a constantly-improving comprehensive approach.

[1] All acronyms are defined in the Glossary.
[2] Class A mishaps are those where there is loss of life, injury resulting in permanent total disability, destruction of an aircraft, and/or property damage/loss exceeding $1 million (Air Force, 2001).

2 Overview

The research effort reported herein was a typical SBIR: a 6-month Phase I proof-of-concept project followed by a 2-year development project. Because Alion/MA&D's niche in the human factors R&D market is human performance modeling, that is how we approached the problem. In Phase I we modeled two common SD illusions: Leans and Coriolis. We selected those illusions because Leans is the most common SD illusion, and is a slow-onset insidious hazard. Coriolis, on the other hand, is a quick onset illusion and often fatal. Thus, we strove to capture opposite ends of the SD illusion spectrum, in a sense. (In actuality, SD illusions are multi-dimensional, so timing and severity are just two ways to potentially categorize them.)

Proving the value of our approach in Phase I led directly into Phase II, where we more fully developed our concepts, models, and tools. It is important to note that one commonly known benefit to computer modeling of anything is that the modeling team learns a great deal about the phenomenon being modeled and the problem being addressed by the modeling effort. So, even if we had been unsuccessful with our approach, we would have contributed to the research base.

The emphasis of this report is on Phase II. Readers interested in the full evolution of our thought process should review our Phase I final report (Small et al., 2004).

As we evolved our approach and discussed ideas with colleagues and collaborators (see Acknowledgments), we began to see a theme: Detection and Aiding (Figure 1). Readers will notice this theme throughout this report. Detection means all of the work done to understand the nature of SD illusions and to detect them within flight data, simulator data, and even experiential anecdotes. Aiding refers to our approach to minimizing SD illusion severity by applying countermeasures and otherwise aiding pilots – helping them to recover from illusions. Figure 1 also highlights the project's two products – spatial disorientation analysis tool (SDAT), and spatial orientation aiding system (SOAS) – which are actually combined into a single software system as a deliverable product.

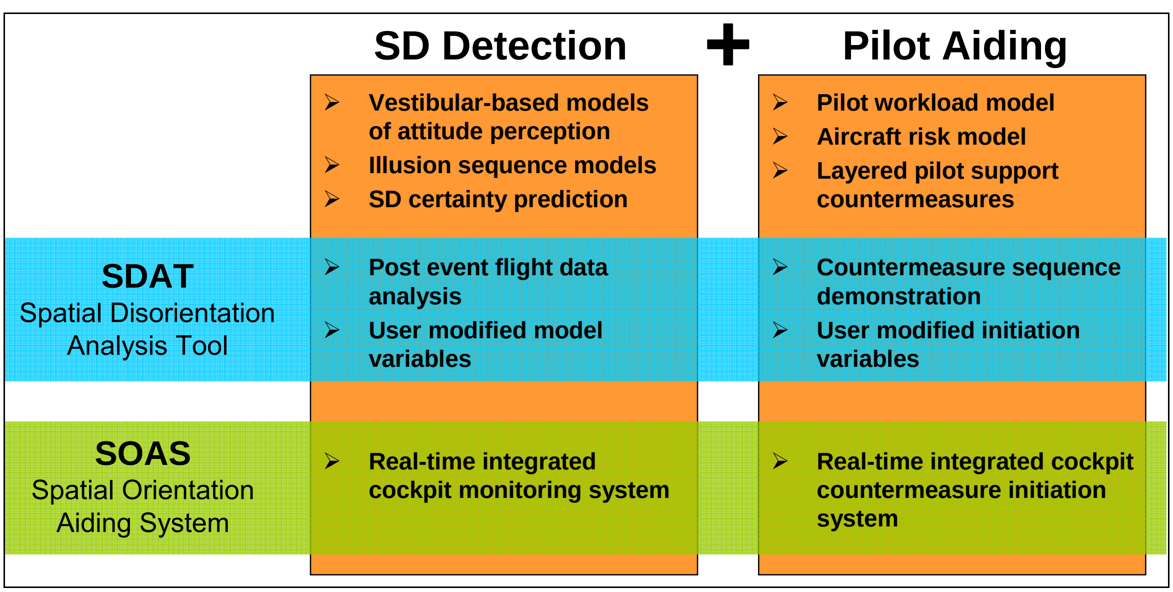

Figure 1. Overview of project's technical approach.

We would have considered ourselves successful if we had only been able to reliably detect SD illusions. But, as human factors professionals whose goal is always to help users (in this case, pilots), we wanted to do more. Detecting SD is necessary, but not sufficient, to saving lives. To illustrate this point, our detection system could fairly reliably inform pilots that they have SD. But, merely informing them of the hazard does only half the job – and the less important part at that (in our view). Because SD is, by definition, disorienting, it is vital to help the pilots minimize the adverse consequences of the SD event. Therefore, we also explored ways to help pilots recover from SD when it happens (not if it happens). And, ultimately, that was our customer's primary goal: to devise a set of integrated multisensory methods to help pilots maintain spatial orientation (SO). If pilots maintain SO all the time, then they would never succumb to SD. While this is a noble goal, it is unrealistic. The vast majority of pilots suffer from SD at some point in their flying careers (Previc & Ercoline, 2004); it is nearly unavoidable. As part of a comprehensive approach, it is simply insufficient to combat SD from a pure prevention standpoint – plus such an approach is doomed to failure, as already emphasized. Therefore, we needed to pay attention to detection and aiding.

Some have argued that, by removing human pilots from aircraft and using UAVs for missions, we will eliminate the SD problem. This is wishful thinking, as the accident rate of some UAVs attest. Some UAVs experience a near 50% loss rate due, in large part, to visual display illusions during the landing phase of the mission. So, removing human pilots from aircraft does not solve the SD problem, it merely shifts the problem to those SD illusions from which UAV operators suffer.

SD detection relies upon models that reflect our understanding of specific SD illusions, as well as the ways pilots get into trouble from a spatial orientation perspective. There is a vast literature base that helped us understand SD. However, it has some gaps, which naturally prompted us to conduct experiments to fill some of the gaps. Our experimental results fed directly into our modeling effort, and also served to expand the research base. Appendix A details all of our experiments in journal papers that we have submitted for publication.

Aiding pilots who suffer from SD has also received considerable research attention. The typical methods are to use enhanced visual displays, novel auditory displays, and even haptic or tactile displays. Again, we found gaps in the research base, and so designed and conducted experiments to test our thoughts about the best way to help pilots. Appendix A also details these experiments and results.

The culmination of our approach to improving detection and aiding is a software tool that serves both purposes. We call the detection and analysis portion SDAT – spatial disorientation analysis tool. It is explained in Chapter 3, and further detailed in its User Guide (Alion, 2006). The emphasis of SDAT is on *post hoc* data set analyses.

The aiding portion is SOAS – spatial orientation aiding system. SOAS is intended to be a real-time *in situ* cockpit system that helps pilots recover from SD and to avoid its bad consequences (e.g., crashes). Importantly, SDAT and SOAS use the same code base which runs faster than real time, and we used SDAT extensively in Phase II to analyze actual SD mishap flight data sets

(Section 3.5). Due to schedule and budget limitations, we were unable to test SOAS in flight with real pilots. That is our greatest disappointment. However, adequately instrumented aircraft are uncommon, therefore difficult to schedule, and they are expensive. Near the end of Phase II, we found one at the University of Iowa, and hope to use it in Phase III, if we are fortunate enough to attract sufficient additional funding.

The last chapter of this report (Chapter 4) recommends many steps to consider in Phase III or in any similar follow-on research. While we are very proud of our results, we recognize there is still much to do in both areas – detection and aiding. Aiding, especially, needs attention, as certifying cockpit systems is an intensive multi-year effort.

2.1 Technical Approach

The project team's technical approach was to understand and model SD, and to devise multisensory countermeasures for helping pilots who, despite the best intentions and pre-mission preparations, experience SD; it is a nearly unavoidable problem. Therefore, we had to understand the root causes of SD, scope the problem to fit within a Phase II SBIR project, model illusions, develop a tool (SDAT) to try our detection algorithms, test it and refine it, and then focus on the aiding component by developing a countermeasure or compensatory piece (SOAS) once we felt we had done an adequate job with the detection challenge. Even though this description implies a linear progression from start to finish, in actuality it was an iterative process with multiple feedback loops, some dead-ends, and the usual trial-and-error efforts of a typical R&D project. That is, we tried some detection and aiding ideas in parallel, saw what worked and what did not, and then iterated until we ran out of time and budget.

We learned fairly early in the research that we could not hope to detect every known SD illusion. For example, there are many visual illusions that simply do not lend themselves to detection via a flight data processing approach, no matter how many novel sensors we cared to imagine. Therefore, we scoped the effort to focus on vestibular illusions, and, more specifically, on those that could be detected via flight data processing – data that are available on today's aircraft or via today's national airspace system (NAS) technologies (e.g., enroute and terminal radars), rather than some hypothetical future aircraft equipped with pilot physiological monitoring, for example.

Section 2.3 details the physiology that we learned primarily during Phase I; we continued to add to our knowledge during Phase II, especially with the publication of the Previc and Ercoline book (2004). The physiological knowledge directly supports our detection (modeling) efforts. We determined that there are four ways that a pilot's vestibular system can be "tricked" by typical aircraft motions. These four ways are:

1. Sub-threshold rotations that the vestibular system does not register, even though the aircraft moves. These sub-threshold rotations typically occur around the roll axis of the aircraft.
2. Sustained rotations that yield washout, so that the vestibular system stops sensing the rotation, even though the aircraft is still rotating. Washout typically occurs in the yaw (heading) plane of aircraft motion.
3. After washout, returning to straight flight (as occurs when rolling out from a sustained turn) yields illusory rotation. That is, the vestibular system perceives a turn in the opposite

direction from the original turn. Eventually, there is washout of the illusory rotation; this illusory washout occurs at the same rate as washout from an actual turn.

4. Changes in airspeed yield perceptions of pitch changes. Decelerations feel like pitching down; accelerations feel like pitching up from the actual pitch angle.

Our models and vestibular attitude calculations constantly compare the actual aircraft motions (and resulting attitude) with what the pilot's vestibular system perceives. Differences between actual and vestibular-perceived motions and attitudes are the basis for detecting SD. A more detailed explanation of the human vestibular system is in Section 2.3. More details about our modeling and vestibular attitude calculator (VAC) methods are in Section 3.1.

2.2 Phase I Highlights

In Phase I of this SBIR, we accomplished the following major objectives:

- A literature search, including Russian literature, which formed the foundation of our quantitative, model-based approach. An annotated bibliography is Chapter IX of the Phase I final report.
- Designed and developed detection models for the Leans and Coriolis illusions. The Leans model worked with the actual F-16 data that we received from the Air Force Safety Center (AFSC) within the last weeks of the Phase I technical work. We were especially delighted that our SD Aiding system (the name was changed to SOAS in Phase II) was robust enough to detect instances of SD within this data set in a sensible, realistic manner.
- Enhanced Wickens' (1984) Multiple Resource Theory to account for the other senses central to this multisensory effort. We called the resulting "theory" SAVVOY in honor of Dr. Wickens' location in Savoy, Illinois (at the University of Illinois' Aviation Research Laboratory). The newly included senses were somatic, vestibular, and olfactory. A model of pilot workload, using hypothetical (but realistic) SAVVOY scores, influenced the SD countermeasures applied by our SD Aiding System. The acronym SAVVOY represents somatic, auditory, visual, vestibular, olfactory, and psychomotor. Pilot workload is an important factor in determining which aiding countermeasures to apply, and when. For example, when there is radio chatter, we suppress audio countermeasures in favor of visual and tactile ones.
- Invented an SD Icon to be an intuitive representation of the aircraft pitch and roll. While we originally hypothesized the SD Icon as a status display, we determined that it might be more valuable as a command display. Phase II aiding experiments tested the value of the Icon.
- Most importantly, we delivered a working SD Aiding prototype that served as an excellent foundation for Phase II development and testing. The software grew considerably in Phase II. Both detection and aiding were improved.

Figure 2 summarizes and highlights Phase I. It emphasizes the aiding part of the SD challenge because that is what made for a compelling demonstration to help us win Phase II. It proposed layered or sequential multisensory countermeasures, including visual, auditory, tactile, and olfactory cues, as well as combinations of these to help pilots notice their unusual attitude (due to SD) and prompted their recovery actions. As a proof-of-concept, we did not have to make sure that everything worked in our conceptual prototype, but it did. We accounted for the pilot's multisensory workload and the aircraft situation. For example, if the aircraft was about to crash, the countermeasures were more intrusive (e.g., combined visual, audio, and tactile recovery commands). If the SD event happened at high altitude, such that its consequences were less severe, then the countermeasures were less intrusive (e.g., visual cue only). In either case, the assessment of the confidence level that the modeled SD illusion was actually occurring also contributed to the prototype's triggering of countermeasures.

Figure 2. Phase 1 aiding concept screen shot.

2.3 SD Physiology Background

In addition to initiating detection and aiding concepts in Phase I and carrying them forward into Phase II, another important contribution from Phase I into Phase II is the physiology of SD – with emphasis on the human vestibular system. The goal of modeling SD illusions in real time is to compare actual aircraft attitude to our inference of the pilot's perception of aircraft attitude. It is the latter that our basic models capture via our *Vestibular Attitude Calculator* (VAC). The relevant physiology of SD follows so that readers do not have to look elsewhere for this vital background information.

The eyes, the most important source of motion information to the human brain, send information to the pilot's brain about the aircraft's position, velocity, and attitude relative to the ground. The overwhelming reliance on visual cues over those from other senses, when there are sufficient visual cues, is called *visual dominance*. Visual cues are ideal for spatial orientation on clear days in VFR conditions with a well-defined horizon. But, when visibility is poor (e.g., during night flying, or in IMC), pilots can experience SD illusions. Even on a clear VFR day, the eyes can "play tricks" (e.g., runway and approach visual illusions).

The inability of pilots to accurately and intuitively perceive aircraft position without reliance upon visual cues (from flight instruments or the outside world) is a major crux of the aviation mishap problem. Maintaining spatial orientation cannot be done in present-day flight operations unless one is attending to the appropriate visual cues. Unfortunately, many of an aviator's distracting secondary flight tasks are also of a visual nature, so continuous attention to one's spatial orientation cannot be maintained using current visual displays. Furthermore, attention can also be diverted to non-visual sources as well (Wickens, 2002), for example the distraction of voice communications or problem solving. Holmes et al. (2003) identify "distraction/task saturation" as an important factor in their list of causes of spatial disorientation. The problem concerning the allocation of limited attentional resources is compounded by the fact that attentional resources will be drawn to more natural and salient body (vestibular) cues concerning orientation, which in the environment of flight are not veridical. In other words, the problem of SD in flight is not caused merely by attentional limitations; rather, the problem is the formation of an incorrect, yet persuasive, subconscious tendency to rely upon vestibular orientation cues. The typical SD mishap occurs when visual attention is distracted from the aircraft's orientation instruments and the horizon is not visible or not being monitored (McGrath, 2000).

Because a realistic, achievable approach to modeling SD requires understanding and modeling the vestibular system, the following section highlights the human vestibular system and its behaviors during fixed-wing aircraft flight.

2.4 Vestibular System

The parts of the vestibular system on which we focus are the semicircular canals, and the otoliths or vestibular sacs in the inner ear (Figure 3). The semicircular canals are filled with fluid that indicates bi-directional rotation in the pitch, roll, and yaw axes via the cilia, or hair cells, within each canal. The canals are actually accelerometers that sense changes in velocity. Figure 4 shows the role of the semicircular canals in the three dimensions of flight. The otoliths, connected to the base of each semicircular canal, respond to linear accelerations and decelerations.

As rotational motion occurs, the cilia (hair cells) in the canals bend in response to the relative motion between the canal walls, to which the cilia are attached, and the fluid within the canal. The fluid's inertia provides initial resistance and bends the cilia, which informs the brain of the acceleration axis and the magnitude of angular acceleration. After undergoing sustained and constant angular motion, however (e.g., continuous heading change in a standard rate turn), the fluid within the canals begins to rotate at a velocity corresponding to the body and head. As a consequence, there is no longer relative motion between the cilia and the fluid within the canals, the cilia are not bent, and so no sensation of motion is sent to the brain. This phenomenon is called "washout" and has important implications for spatial disorientation. This washout occurs after approximately 10-15 seconds of sustained rotary acceleration (Gillingham & Previc, 1993).

It is important to note that there is individual variability for washout timing, as well as for the initial detection of motion change, described next. This variability applies between people and within an individual under varying circumstances. It is this variability that makes modeling the vestibular system very challenging, which complicates the detection component of our approach. And, one can imagine that if the detection component is difficult, then the aiding portion is even more so.

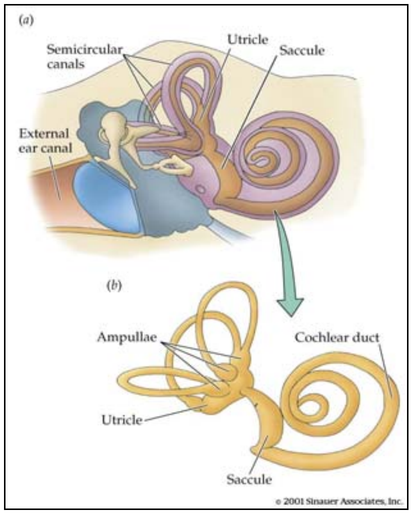

Figure 3. The structure of the outer, middle and inner ears showing the location of the semicircular canals (Rosenzweig, et al., 2002, pg. 67)

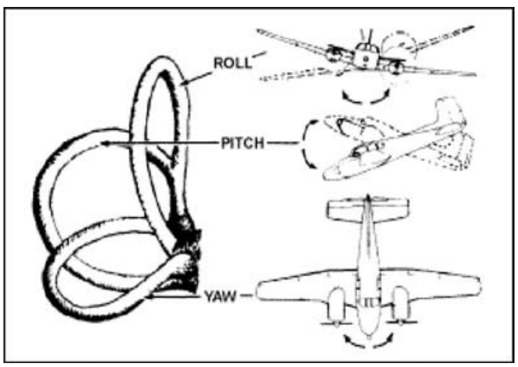

Figure 4. The role of the semicircular canals in the perception of 3-dimensional motion (US Army, 2000).

Another important term to SD research is Mulder's Law (DeHart & Davis, 2002), which describes a threshold (called Mulder's Constant) below which accelerations are not sensed by the human vestibular system. For an angular acceleration to be perceived, the product of the intensity or magnitude of acceleration (deg/s^2) and time (seconds) of application must reach a threshold value. The best way to illustrate the meaning of Mulder's Law is with a few examples, where Mulder's Constant is assumed to be 2.5°/sec:

1. If a person experiences an acceleration of 1°/sec^2 for 1 sec, he or she will probably not sense that acceleration because the product (1°/sec) does not exceed Mulder's Constant.
2. If the same acceleration occurs for 3 sec, however, it will likely be detected (because the product, 3°/sec, exceeds Mulder's Constant).

3. Even a large acceleration of 10°/sec^2 will not be felt, if its duration is less than 0.2 sec. The same acceleration will be felt, if its duration is 0.25 sec or greater.

It is important to note that not all humans have identical thresholds and various researchers have determined slightly different threshold values. The following is a list of the most commonly accepted threshold values:

- Mulder (Guedry, 1974): 2.5°/sec for all three axes.
- Stapleford (1968): 3.2°/sec for roll; 2.6°/sec for pitch; and, 1.1°/sec for yaw.
- Oman (2005): 1.5°/sec for all three axes.

While the semicircular canals sense rotary motion, the otolith organs sense linear accelerations. Here, in the presence of linear acceleration, the cilia within the otoliths will bend opposite to the direction of acceleration. This angle of bend, relative to the orientation of the organ, signals the magnitude of acceleration. The orientation of the cilia is affected by gravitational force as well as by accelerations (Howard, 1986). Hence a linear forward acceleration will produce the same vestibular sensation as a tilt backward, producing the phenomenon of the *somatogravic illusion* (Gillingham & Previc, 1993; Tokumaru et al., 1998), in which pilots who execute a rapid acceleration (for example, on a missed approach) may incorrectly perceive a pitch-up motion.

As with the semi-circular canals, the otoliths have thresholds of detection. In the Z (vertical axis) the threshold is 0.15 m/s^2; for both X (roll) and Y (pitch) axes the threshold is 0.06 m/s^2 (Previc & Ercoline, 2004, pg. 54). As with rotational motions, we assume there is individual variability.

2.5 Phase II Highlights

Starting with a solid foundation from Phase I in terms of theory and a working prototype, we began Phase II with a primary goal of validating our models, via experiments, and adjusting the models as needed to incorporate experimental results, as well as the new knowledge gained from collaborators and from the literature. Some experiments proceeded as planned; others experienced minor or major glitches. Regardless of the execution details, we made the most of the resulting data. Without doubt, however, the most valuable Phase II experiences were when we analyzed actual flight data from military and civilian accidents where SD was believed to be a contributing factor. Section 3.5 describes our analytical process and summarizes the results. Of the 12 data sets analyzed, SDAT results agreed with the safety investigation findings for six; three were inconclusive; two disagreed; and one data set was corrupted and unusable. For the two where SDAT results disagreed with the official findings, additional knowledge about the nature of the flights would have suggested that SDAT was inappropriate to use because those flights involved disorientation not related to vestibular illusions.

We did not accomplish as much with SAVVOY as we had hoped. Due to our emphasis on SD detection, the aiding portion of our R&D necessarily received less emphasis. SAVVOY influences SD countermeasures because SOAS favors modalities that are not (or less) loaded than others. Despite this shortcoming, we conducted two experiments whose focus was on multisensory countermeasures.

About halfway through Phase II, we realized that some of our innovative work might be patentable. After obtaining permission from our customer and her contracting experts, we hired local patent attorneys. The result is our US patent application at Appendix D. As of this writing, we have received no feedback about our application from the Patent and Trademark Office. When we do, we shall keep our customer apprised of significant developments.

We designed and conducted two other experiments whose primary focus was on detection. All of the experiments are explained later, with emphasis on how we used the results. In the case of the detection-oriented experiments, results directly impacted our SDAT/SOAS models. For each formal experiment we submitted a journal article. Those articles (some accepted, some still in review) are in Appendix A.

Furthermore, we presented the highlights of our research at several professional conferences. The first was HCI-Aero in Toulouse in June 2004; next was WinterSim in DC in December 2004; following was the AIAA-ATIO conference in September 2005; the last was AsMA in May 2006 in Orlando. We also exhibited at AsMA in May 2005 in Kansas City. It was there where we met many of the AFSC people with whom we would later collaborate on SD mishap analyses. (We also attended AsMA 2004 in Anchorage, but that was between Phase I and Phase II and so not under contract funding.) The final noteworthy publication-related item is an article published in a Russian aerospace bulletin in the April-May and June-July 2005 issues; it is a lengthy abstract from our Phase I report translated into Russian by the editor and his staff.

3 Accomplishments

Re-visiting the dual theme of detection and aiding, the following sections of this chapter start with detection, and then address aiding. First we explain our modeling approach (Section 3.1), then our aiding philosophy (Section 3.2), followed by the experiments we conducted to support each component of the detection-aiding challenge (Section 3.3). After that are sections describing our software (3.4) and our SD mishap data analyses (3.5).

3.1 Modeling

Modeling focuses mainly on SD detection, although some workload modeling determines countermeasure triggering. The pilot workload modeling is much more simplified than originally envisioned at the start of Phase II. It can best be summarized by stating that SOAS suppresses audio countermeasures when the pilot's audio workload is high. Other modeling relates to triggering countermeasures based upon the state of the aircraft, such that more intrusive countermeasures trigger when the situation is more dire (e.g., imminent crash). First, we present extensive detail of our detection modeling in the following sub-sections.

Spatial Disorientation *Detection*

One of our goals for this work has always been to support the pilots during actual flight. As such, the system for detecting spatial disorientation has to function with the information available within the cockpit. Likewise, the models of spatial disorientation were limited to physiology that responded to aircraft motion. Therefore, the SD detection system is a combination of aircraft flight dynamics and vestibular perception models.

Figure 5 shows the high level process for the detection system. The vestibular-based models predict the perception of roll axis and yaw axis (heading) rotation as a function of semi-circular canal response to actual aircraft angular accelerations. Pitch angle perception, using an otolith model, is based on the aircraft's longitudinal linear accelerations. The SD illusion models use a combination of flight dynamics and perceived attitude values to determine when a pilot may be experiencing a specific SD illusion (i.e., Leans, Graveyard Spiral, Coriolis).

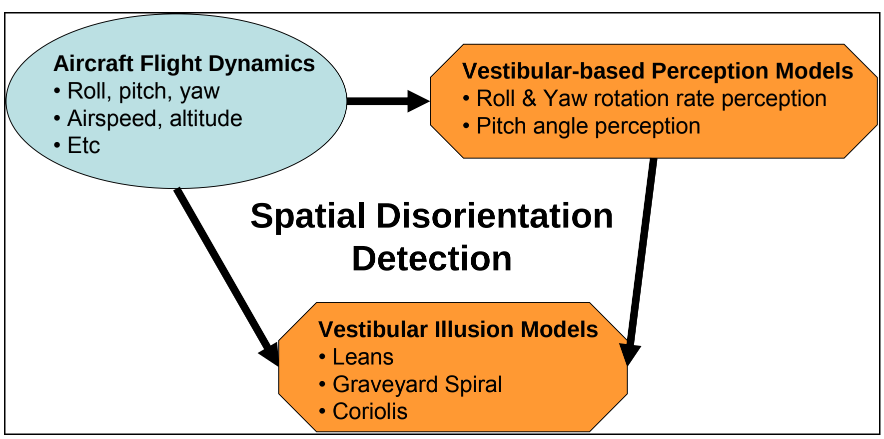

Figure 5. SD detection system flow.

The purpose of the vestibular model is to predict the attitude cues provided to the pilot by the vestibular system in the absence of visual orientation cues. The model uses basic aircraft flight dynamic data (available to accident investigators, as well as aboard modern aircraft in real-time within the avionics system) and the associated responses of the vestibular system. The angular rotation model uses Mulder's Law and perception threshold values to determine which roll and yaw angular accelerations are perceived by the pilot. The concept of washout is used to predict the loss of the sense of rotation. The pitch perception model uses linear accelerations to calculate the pitch information provided by the otoliths. Data values at a fairly high sampling rate (4-8 Hz) for roll and pitch angles are commonly available from modern aircraft. For the purpose of this work, we use the term "yaw rotation" to denote the rotation of the aircraft as its heading changes. For each time period, the yaw rate and acceleration are calculated as a function of the change in heading.

Initial Rotation Perception - Implementing Mulder's Law

Mulder's Law (Guedry, 1974) combines the magnitude of an angular acceleration and the time of application to determine if a change in the attitude of the aircraft is sufficiently high to be perceived by the vestibular system. In essence, larger accelerations over short periods of time and smaller accelerations over long periods of time can both be perceived. Applying Mulder's Law to any single time slice of flight data is relatively simple. The result of multiplying the rotational acceleration by the time interval is compared to the threshold value. If the product is above Mulder's Constant (where we use Oman's (2005) recommendation of 1.5°/sec for each axis), the change in attitude is perceived by the vestibular system. This value-by-value implementation is referred to as "instantaneous Mulder's."

Table 1 shows yaw data sampled at approximately 1 Hz and the resulting instantaneous Mulder's calculation. The reader will notice that there is a change in rotation (a left turn) starting at around 33 seconds (line 4) and that the turn rate stabilizes by about 46 seconds (line 16). Also notice that none of the instantaneous Mulder's calculations reach the 1.5 threshold level. Using the instantaneous calculation, we would predict that a pilot deprived of visual input would likely not feel the acceleration into this turn (if it was coordinated; i.e., no slip or skid). The result would be an approximately 3.5 deg/s discrepancy (delta) between actual and perceived yaw rotation.

A more complex implementation is required to model Mulder's Law calculations for durations larger than the sampled data interval. Again, the idea is that small accelerations can be perceived if they occur for a long enough time. Our implementation involves averaging multiple acceleration values and then multiplying by the time duration. For example:

> Lines 4 & 5 have accelerations of -1.0 and -.85
> The average is -0.93 deg/sec^2
> The time interval of application is 34.6 – 32.42 = 2.18 seconds
> The Mulder's Law calculation is then 0.93 * 2.18 = 2.03

This combined acceleration is greater than the 1.5 threshold so the model predicts that the corresponding change in velocity over this time period would be perceived. The amount of that change is calculated by the difference in velocity across the associated lines of data (2.08 - 0.06 = 2.02 deg/s).

Table 1. Yaw data at approximately 1 Hz sampling rate.

Line #	Time	Heading	Yaw Rate	Yaw Acceleration	Instantaneous Mulder's
1	30.25	200.4	-0.01	0.0	0
2	31.34	200.4	0	0.01	0.01
3	32.42	200.33	-0.06	-0.06	-0.06
4	33.52	199.05	-1.16	-1.0	-1.1
5	34.6	196.8	-2.08	-0.85	-0.92
6	35.66	193.96	-2.68	-0.57	-0.6
7	36.75	191.22	-2.51	0.16	0.17
8	37.85	188.26	-2.69	-0.16	-0.18
9	38.95	185.52	-2.49	0.18	0.2
10	40.03	182.68	-2.63	-0.13	-0.14
11	41.12	178.72	-3.63	-0.92	-1
12	42.2	173.92	-4.44	-0.75	-0.81
13	43.3	168.88	-4.58	-0.13	-0.14
14	44.4	165.01	-3.52	0.96	1.06
15	45.5	161.83	-2.89	0.57	0.63
16	46.59	158.04	-3.48	-0.54	-0.59
17	47.68	154.27	-3.46	0.02	0.02
18	48.78	150.45	-3.47	-0.01	-0.01
19	49.89	146.61	-3.46	0.01	0.01
20	50.97	142.88	-3.45	0.01	0.01
21	52.08	139.03	-3.47	-0.02	-0.02

One problem with this method is to know when to stop combining accelerations. According to Previc and Ercoline (2004) Mulder's Law holds true for accelerations less than 10 seconds in duration. As such, the model limits the number of combined accelerations to a 10-second period. However, the model does not simply combine each 10-second interval for a result. For example, combining very low accelerations (lines 1-3) with larger ones (lines 4-5) could result in masking perceived changes. Our answer is to check the combination of each successive acceleration, in turn, to determine if it reaches the threshold value. The logic proceeds as follows:

Given any data sequence:

- If Instantaneous Mulder's (IM) of line 1 is above threshold, then apply the change to the perceived attitude value and go to next line of data.
- If IM1 is below threshold, then do not apply any change to the perceived attitude value and go to next line of data.
- If IM2 is above threshold, then apply the change from 2; ignore 1 and increment.
- If IM2 is below, then check the combination of 1&2.
- If combined 1&2 is above, then apply the change and increment.
- If combined 1&2 is below, then do not apply a change; check the next line.

Extending this sequence to a long series of sub-threshold individual and combined accelerations, the calculation sequence is:

check line 1
check line 2
check 2 & 1

check 3
check 3 & 2
check 3 & 2 & 1
check 4
4, 3
4, 3, 2
4, 3, 2, 1
etc.

This process allows the model to check each subsequent acceleration without unnecessarily combining it with very low accelerations that might mask a perceived acceleration while still checking long sequences of low accelerations. If combinations of up to 10 seconds are checked without exceeding the detection threshold, the algorithm drops the first value in the sequence and includes the next one. This way it acts as a 10-second sliding window of perception.

However, using this process could yield computations that assess too many combinations, thus jeopardizing real-time performance (which is a huge concern for SOAS, less so for SDAT). If the sampling rate is 1 Hz, then VAC could check the sequence for ten lines of data. The number of calculations is [(n * (n-1))/2], so evaluating 10 lines of data requires 45 calculations. If the sampling rate is 2 Hz then 190 calculations are needed. Since aircraft data are sometimes sampled at frequencies of 8 Hz or more, processing time for a cockpit system becomes an issue. To shorten the sequence, the algorithm uses the assumption that very low accelerations will never be perceived even when combined for 10 seconds. For example, accelerations below 0.1 are not combined and the calculation increments to the next line of data.

Rotation Perception Decay Model

The next step in the rotation perception model is the representation of washout. During constant rotation, such as a turn, the rotation perception information from the semi-circular canals progressively diminishes. The characteristic of this decay can be model using an exponential decay function. Our model uses the formula:

$N(t) = N_o e^{-\lambda t}$, where:

N_o is the starting rotation value;
t is the time since the start of the decay;
λ is the **decay constant**; and, therefore,
$N(t)$ is the perceived rotation at time t.

In the example in Figure 6, the perceived rotation value has reached 5 deg/sec. After approximately 2.5 seconds the decay is approximately 3 deg/sec, so the perceived rotation rate is only 2 deg/sec. By about 8 seconds the sense of rotation has decayed completely.

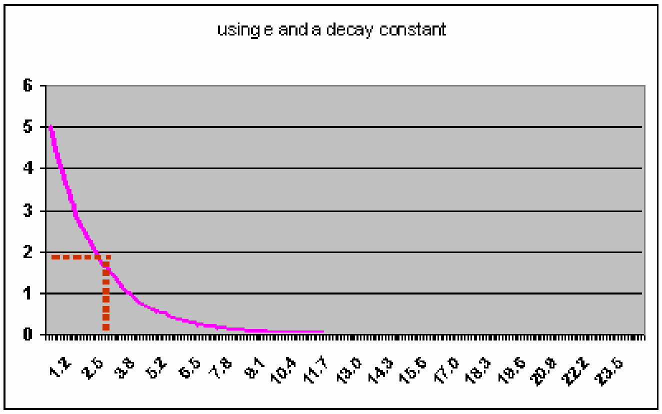

Figure 6. Exponential rotation perception decay example.

The decay constant in the formula is used to change the rate of decay (shape of the curve). Vestibular system research provides a range of time over which complete washout seems to occur. For example, Previc and Ercoline (2004) suggest about 10 sec, whereas Guedry (1974) suggests that washout may take considerably longer: 20-30 sec. However, these values do not support the development of a decay rate across different levels of initial rotation perception. The results of one of the experiments performed during this project (Section 3.2) were used to calibrate the decay model. A decay constant value of .12 in the decay formula best represents the results of the decay duration from this experiment.

The determination of when to start and stop any particular rotation decay sequence (or what constitutes constant rotation) uses the Mulder's-based acceleration perception model. For the purpose of the model, constant rotation is defined as any sequence of accelerations that are below the vestibular detection threshold. If the Mulder's calculation determines that an acceleration is below threshold, then the starting value of rotation for the decay calculation is the current perceived value. Decay continues until an above threshold acceleration occurs.

Combining Perception and Decay

Much of the research of angular acceleration thresholds seems to have been applied from the point of zero rotation. A stationary subject is accelerated in a specific angular plane at different rates and the threshold at which they sense the rotation is recorded. We know of no study that tried to determine detection thresholds for participants who start from a non-zero angular velocity. It is possible that threshold perception values could be different when already rotating as apposed to starting from zero rotation given the non-linearities of cupolary response. Our assumption is that we can use the same threshold values to apply velocity changes to perceived values whether or not the pilot is already sensing rotation. The extension to that assumption is that the velocity change associated with a perceived acceleration is additive to the current perceived value.

The vestibular perception model combines the implementation of Mulder's Law with the decay sequence to calculate the different between the actual aircraft angular rotation and the angular rotation information provided to the pilot through the vestibular system. Figure 7 shows the analysis sequence for the semi-circular canal model for the perception of rotation in yaw and roll. If a specific acceleration is above threshold then the same velocity change applied to the aircraft is applied to the perceived rotation value (i.e., it is noticed). If a specific acceleration is below threshold then the associated small change to the aircraft rotational velocity is not applied to the perceived velocity value resulting in a difference between the actual aircraft (AC) yaw or roll rotation rates and the perceived value of those rotations. For any sub-threshold change, the washout calculation is then applied to predict how much of the sense of rotation is lost for the given time period. For each time period, the model then calculates the delta (difference) between the actual and perceived attitudes.

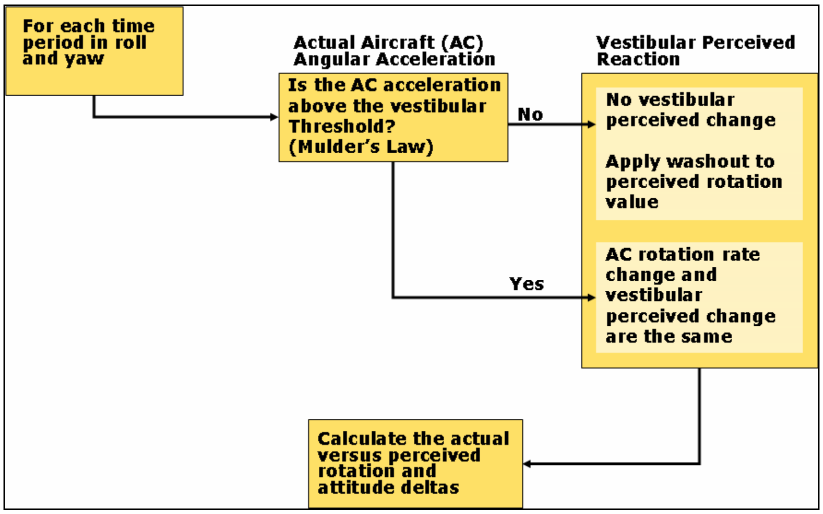

Figure 7. Perceived attitude algorithm sequence.

Actual versus Perceived Rotation Delta Examples

The following two examples show rotation perception deltas predicted by the vestibular model when applied to real flight data. The reader should recall that the perceived rotation values are based on the information provided by the vestibular system without any visual information.

The graph in Figure 8 shows an example of actual versus perceived rotation as calculated by the vestibular model. The data set is approximately three minutes long and shows a long left turn. The blue line in the figure show that the yaw rotation (heading change) reaches a maximum rate of about -5 deg/sec (negative values are left turns). Partway through the turn, the rotation drops to zero before increasing again. The rate of change of the rotation is slow enough to be below the perception threshold value for nearly the whole data set. The red line shows the rotation rate as calculated by our vestibular model. Since the accelerations are below threshold, there is almost no perception of the turn as it occurs. The only supra-threshold movement is at about time 125 when the rotation rate is quickly reduced by about 2 deg/sec. The movement is above the vestibular perception threshold and the pilot would feel approximately 2 deg/sec of rotation to the right (illusory rotation). Then, the movement back to -5 deg/sec rotation is sub-threshold, so it is probably not perceived by the pilot. As such, it is the decay (washout) of the sense of illusory rotation that brings the perception of rotation back to zero a few seconds later. The magnitude of perceived illusory rotation is determined by the magnitude and duration of the original actual rotation, as well as the rate of the deceleration from that rotation, an issue examined in an experiment described in Section 3.3.

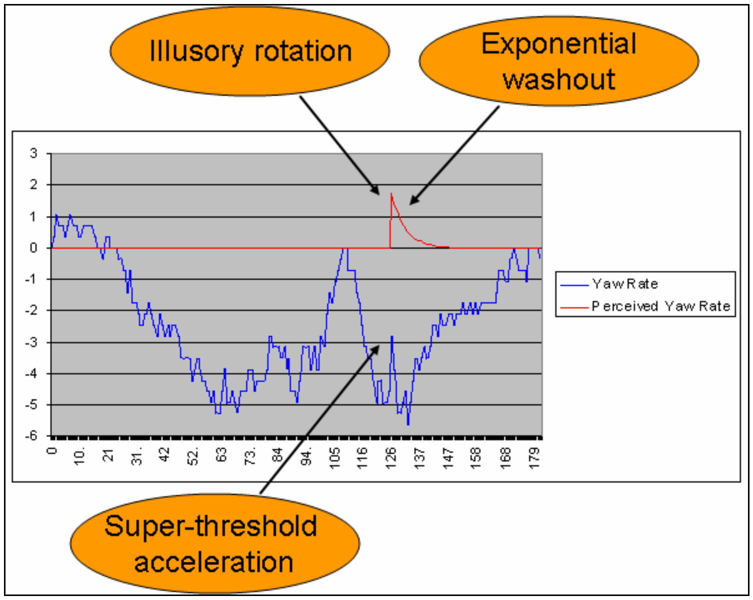

Figure 8. Actual vs. perceived yaw rate example 1.

Figure 9 shows another example of actual versus perceived yaw rotation. Over about 2 minutes, the blue line shows a series of three right hand turns. The rotation rate of the first turn is maintained at about 2 deg/sec. The red line, representing the perceived rotation rate, shows that the initial acceleration at about time 23 is perceived but then washes out to zero perceived rotation by about time 40. The second turn is at a maximum of about 8 deg/sec rotation and again the perception of rotation is gradually lost during the turn. When the actual rotation returns to zero (after rolling out of the turn), the rotational deceleration is above threshold resulting in over 6 deg/sec of illusory rotation in the opposite direction. The final -4 deg/sec of perceived illusory rotation washes out starting from about time 100 and ending at about time 116 while the actual rotation value is about zero for the same time period.

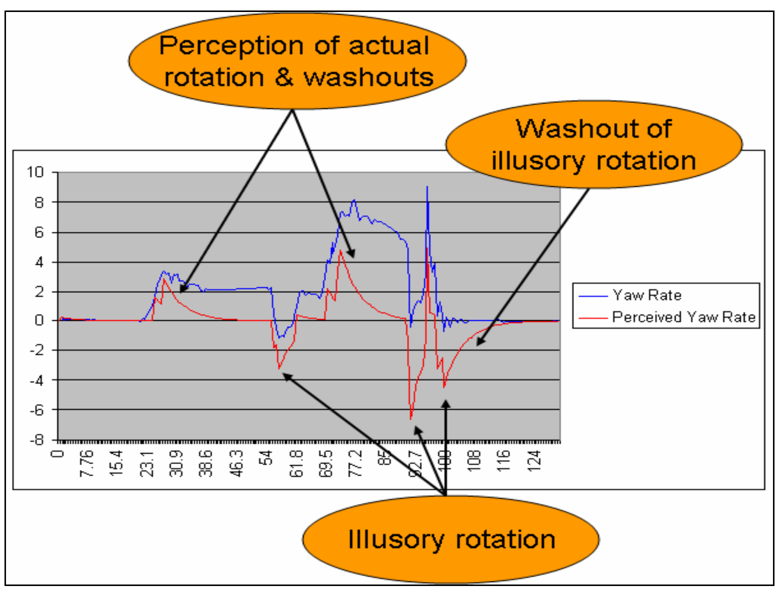

Figure 9. Actual vs. perceived yaw rate example 2.

Pitch Perception Model

The perception of pitch angle is dominated by another organ of the vestibular system call the otoliths. Unlike the semi-circular canals, otoliths respond to linear accelerations. We are particularly interested in the Gx (longitudinal) and Gz (vertical) sensing otoliths, since those are the accelerations most commonly experienced by fixed-wing aircraft pilots. In normal ground activity, this sense is dominated by the acceleration due to gravity, since most self-generated human motion is significantly less than 1 G. Aircraft, however, can create both linear and rotational accelerations that are much higher. The otoliths essentially respond the acceleration vectors. The combination of aircraft acceleration and gravitational vectors can cause the otoliths to create an incorrect perception of which way is down. This is most apparent in the sensation of pitch. A combination of 1 G gravitational vector (Gz) and 1 G linear acceleration vector (Gx), results in the perception of a 45 degree pitch up angle (Figure 10).

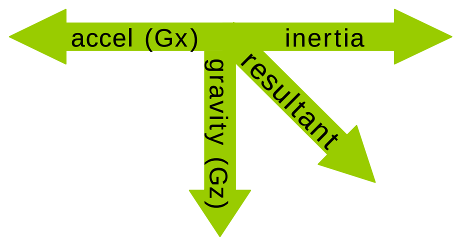

Figure 10. Acceleration vectors and pitch perception illusion (adapted from DeHart and Davis, 2002).

Vector analysis is used to combine the linear acceleration with the acceleration due to gravity to arrive at the perceived pitch angle using the formula: Perceived Pitch = Actual Pitch + ArcTangent(Gx/Gz) (DeHart & Davis, 2002).

For our calculations, Gx is linear acceleration calculated from the change in airspeed and converted to G. Gz is taken from the Normal Load Factor (or similar) value in the data set. By definition, Gx and Gz are orthogonal. Figure 11 shows an example of actual versus perceived pitch based on the model calculation. This data set starts with a takeoff so the actual pitch is 0 until above time 120, then changes quickly to about 12 degrees. The high linear acceleration associated with takeoff causes a feeling of even greater pitch-up during that time period. While the rest of the data set shows a few smaller sustained differences and the occasional high spike, none of the differences are as great as during the takeoff – an expected result.

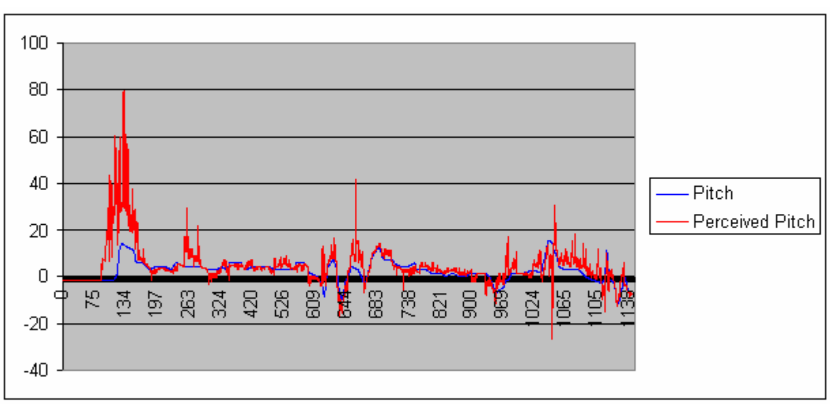

Figure 11. Actual vs. perceived pitch example.

This calculation may only accurate when the aircraft is banked at 30 deg or less. More than that and the perception of 'down' is combined with the bank to the side and the pure pitch calculation may no longer be valid. Although VAC still computes perceived pitch at larger bank angles – at all bank angles, in fact – care must be taken in interpreting the results under these conditions.

Spatial Disorientation Illusion Sequence Models

We know of no way to determine the actual intentions or perceptions of the pilot. As such, it is difficult to determine if a specific SD illusion was experienced based only on flight dynamics. However, looking for specific sequences within a data set and combining those with the perception predictions from the vestibular model, can give us a general indication that an SD problem might be occurring. Three illusion models (Leans, Graveyard Spiral, and Coriolis) are currently used to look for such sequences. They assume that there is no visual information available to the pilot, or that the pilot is not attending to such information. The models are a sequence of events that must occur in a specific order with specific values and time periods. As each event occurs the certainty of SD increases.

The reasons for selecting these three illusions are the same as in Phase I. Briefly, Leans is the most common illusion experienced by pilots, is insidious, and is often a precursor to more severe illusions such as Graveyard Spiral or Spin. Graveyard Spiral is another common SD illusion and lends itself well to modeling and experimental validation (Section 3.3). Coriolis is a sudden incapacitating illusion that seemed worthwhile to address, except for the fact that very few flight data sets contain the pilot's head position data.

The Leans Illusion Model

The most common SD illusion in flight is *the Leans* (Holmes et al., 2003; Benson, 1988), which entails an erroneous feeling of roll. A typical case occurs in the following scenario (Gillingham & Previc, 1993): In instrument flight (horizon not visible), the pilot has very slowly entered a turn, perhaps unknowingly, at a sub-threshold rate so that the semicircular canals provide no sense of rotation and the gravito-inertial force is directly down "through the seat pan," perpendicular to the wings (so there is no sense of being tilted). If the pilot then becomes consciously aware of the aircraft's bank angle (e.g., by looking at the instruments), and intentionally returns the bank to the true level attitude, he or she will now receive a vestibular sensation of an opposite bank. If the pilot continues to rely upon flight instruments to maintain a level attitude, he or she may also *lean* in the orientation of the incorrectly perceived upright (hence the illusion's name). If, instead, the pilot does not rely upon the instruments at this point, but rather the intuitive (vestibular) signal of upright, he or she will return the aircraft to its original misperceived bank angle. Without awareness and conscious correction, the bank can lead to a gradual pitch down attitude, a loss of altitude, and an increase in airspeed. A side-to-side seesawing process of correction and re-entry may also ensue, along with the loss of altitude, until the pilot is so disoriented that recovery to straight-and-level flight is difficult, if not impossible. Such a scenario, in its worst form, ends with a fatal crash.

The model of the Leans is expressed as a timed sequence of events with the certainty of the assessment of the disorientation increasing with each successive event as shown in Figure 12.

The first event is the initiation of a roll at a rate below the vestibular threshold starting from a specified roll angle and rate. The second event is a roll angle change of at least 5 degrees that lasts at least 5 seconds that is reached through continuous sub-threshold movements. If these two events occur in sequence, it is possible that the pilot has not noticed the ensuing roll angle and that there is a difference between the pilot's perceived attitude and the true attitude of the aircraft. As such, the model indicates a possibility of SD but only at a very low confidence level. The third event is the loss of altitude as measured by negative vertical velocity. If this event follows the first two, it is possible that the pilot has also not intended or noticed the loss of altitude and the model represents an increased confidence in its assessment of the Leans. The fourth event is a roll well above the vestibular threshold (e.g., greater than 5 deg/sec). If this occurs following the first three events, it is possible that the pilot has now noticed the roll angle and has quickly corrected back toward level. When this occurs, the pilot's vestibular system will register a roll to an opposite bank angle, again resulting in a difference between the perceived attitude and the actual attitude of the aircraft. At this point the model represents a high level of SD certainty. The final event in the model is the tilt of the pilot's head opposite the perceived roll angle. If this occurs following the other four events, it is likely that the pilot is experiencing the Leans and the model represents an even higher level of SD certainty. Even without pilot head position data for the fifth event in the sequence, this model of the Leans is very good at detecting likely Leans illusions in actual flight data.

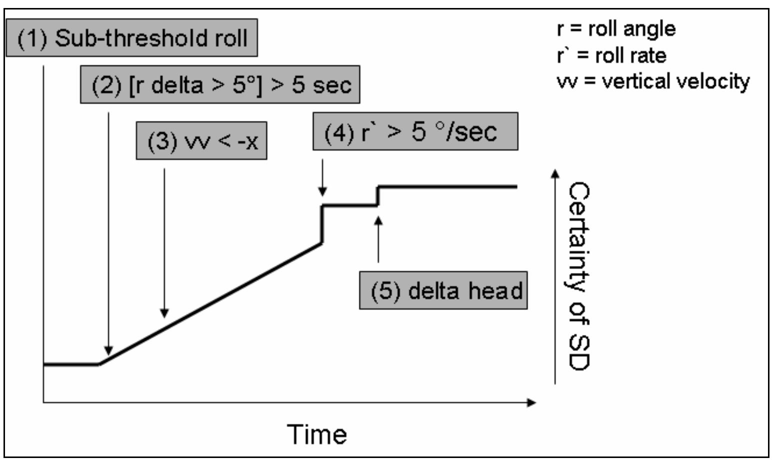

Figure 12. Leans illusion model sequence.

Graveyard Spiral Illusion Model

A somatogyral illusion is "a false sense of rotation (or absence of rotation) that results from misperceiving the magnitude or direction of an actual rotation" (Previc & Gillingham, 1993, p. 59). One such illusion is the Graveyard Spiral in which a misperception of a turn results in a descending and often tightening spiral. The common sequence involves a turn that is held long enough to lose the sense of rotation (i.e., washout). The return to zero bank and therefore straight flight, then feels like a turn in the opposite direction. The pilot then erroneously attempts to reduce the sense of illusory rotation by rolling back into the original turn, typically without increasing pitch to maintain altitude. If the pilot then attempts to arrest the loss of altitude by pulling back on the stick without decreasing the bank angle, the turn tightens and results in a descending spiral.

The Graveyard Spiral illusion model focuses on the difference (we use the term "delta") between perceived yaw rotation as calculated by the vestibular model and actual yaw rotation. Figure 13 shows the model event sequence. Event 1 looks for a perceived yaw rotation that is less than the actual yaw rotation by a specified delta (5 deg/sec). When this situation exists, it indicates either washout or sub-threshold yaw rotation. For the next two events, any reduction in the rotational delta interrupts the sequence and indicates more accurate rotational perception on the part of the pilot. Event 2 looks for a perceived yaw rotation that is greater than the actual provided the rotation delta is maintained. This indicates that the pilot has reduced the actual rotation and is experiencing illusory rotation. Event 3 looks for a perceived yaw rotation that is less than the actual rotation, provided the rotation delta was maintained. This indicates that the pilot increased actual yaw rotation but does not perceive much or any of it. This is indicative of an erroneous roll back to the original rotation in order to reduce the sense of illusory rotation. Event 4 is designed to indicate a loss of control following the other events by a combination of high bank angle and negative vertical velocity. Event 5 looks for the pitch up command that could tighten the spiral.

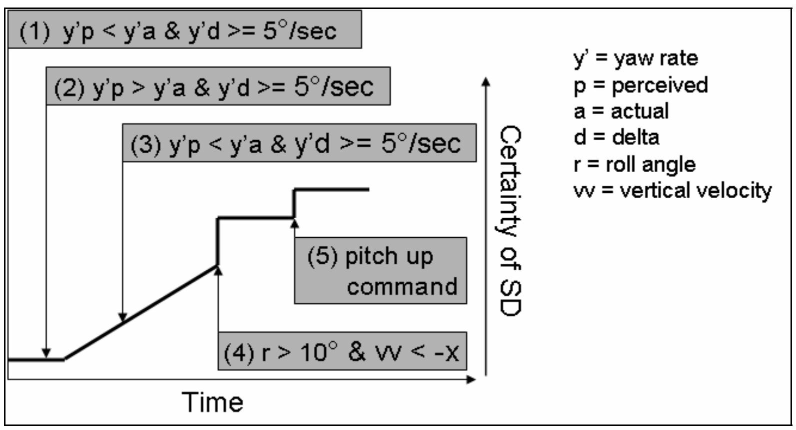

Figure 13. Graveyard Spiral illusion model sequence.

Coriolis Illusion Model

The FAA's Airman's Information Manual (ASA, 1995) describes the Coriolis illusion as the "most overwhelming of all illusions in flight" (page 645). It occurs during "a prolonged constant-rate turn that has ceased stimulating the… [vestibular] system," (i.e., washout) when there is an abrupt head movement that creates "the illusion of rotation or movement in an entirely different axis." The resulting tumbling sensation is nearly incapacitating. The Coriolis illusion often results in the pilot's loss of aircraft control, which can have catastrophic results if there is no other pilot to assume control. The power of the Coriolis illusion to deceive is further supported by the finding in a recent survey that it was the most prevalent of those found in 141 pilots attending a course at Randolph AFB in 1997-98 (Sipes & Lessard, 1999).

This description of Coriolis focuses on rotational washout in the yaw (heading) axis during a sustained turn. The direction of the head motion that then causes the tumbling sensation would be primarily in either the pitch or roll axis. While this is the most likely Coriolis sequence, it is certainly possible for the initiating event of rotational washout to occur in either the pitch or roll axis. The model of the Coriolis illusion developed in this effort looks for an event sequence starting from rotational washout in any of the three axes. However, for the sake of simplicity, this description of the model focuses on the most common version.

Figure 14 shows the model event sequence. Event 1 looks for a perceived yaw rotation that is less than the actual yaw rotation by a specified delta (5 deg/sec). This is the same initiating event as that of the Graveyard Spiral illusion and indicates either washout or sub-threshold yaw rotation. While this delta is maintained, Event 2 looks for a head position angle of at least 30 degrees in either the pitch or roll axis. The combination of these two events could initiate the tumbling sensation. Event 3 looks for a loss in altitude that might indicate that the pilot is having difficulty controlling the aircraft as a result of the first two events. While the occurrence of Event 1 may be quite common in flight, the subsequence occurrence of Events 2 and 3 increases our certainty that the pilot may be experiencing spatial disorientation.

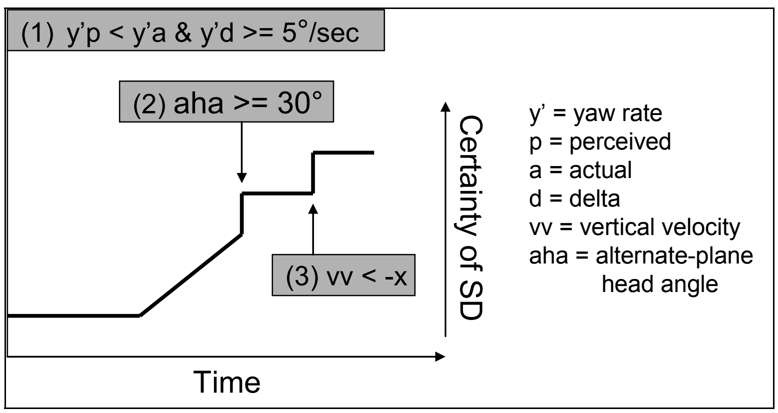

Figure 14. Coriolis illusion model sequence.

The reader should note in the previous illusion model descriptions that increasing certainty level is important to our assessment of the likelihood of SD. The main reason for assessing certainty is to trigger the appropriate SD countermeasures – the aiding portion of this R&D.

3.2 Pilot Aiding

The goal of intelligent multisensory aiding (where SOAS is one example) is to provide countermeasures when pilots need them most, and, perhaps more importantly, to avoid using them when they might be considered annoying or distracting, and unnecessary (if based upon a false inference) rather than helpful. As there are many "bells and whistles" within modern cockpits, it does more harm than good to provide even more cues and alerts to pilots without a high level of certainty that they are, indeed, needed. Even though SOAS is designed to save lives, there is some risk that it may put lives at risk, if it mis-assesses a situation. Consequently, an over-riding dictum within our design is to do no harm. This is especially important during early research, design and development when there may be many latent bugs within the software.

There are three sources of inputs into SOAS's decisions to aid the pilot: SD certainty level, aircraft state (e.g., imminent crash), and pilot SAVVOY workload levels. The following figures depict these decision factors and are unchanged from Phase I; they also reflect the philosophy evolved during the Pilot's Associate program (Hammer & Small, 1995) and related Hazard Monitor R&D (Bass et al., 2004) where the concepts of remediation (i.e., applying actions to remedy a situation) and avoiding the adverse consequences of a situation were paramount.

Figure 15 is an overview of an SD event. The boxes at the left and right signify assessments of the start and finish of an in-flight SD event. The following three figures amplify the situation nodes between the starting (detection) and the finish (termination) boxes.

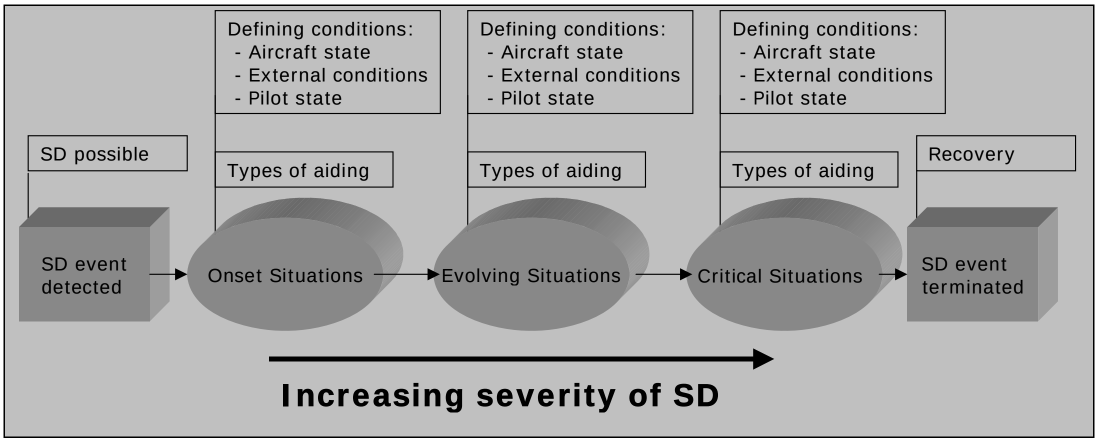

Figure 15. SD remediation network - overview.

There are three categories of situations of concern, each represented with its own figure (interested readers should consult the Phase I final report and/or the listed citations for further information):

- SD Onset situations: Emphasis on prevention (Figure 16)
- SD Evolving situations: Emphasis on helping pilot recognize and recover (Figure 17)
- SD Critical situations: Emphasis on recovery (Figure 18)

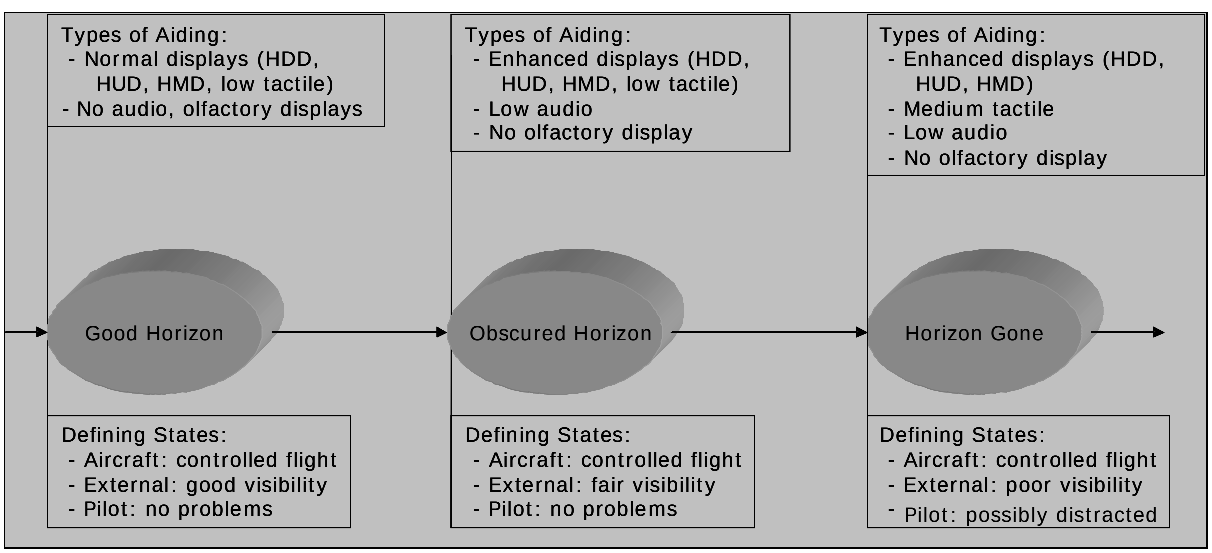

Figure 16. SD Onset remediation network.

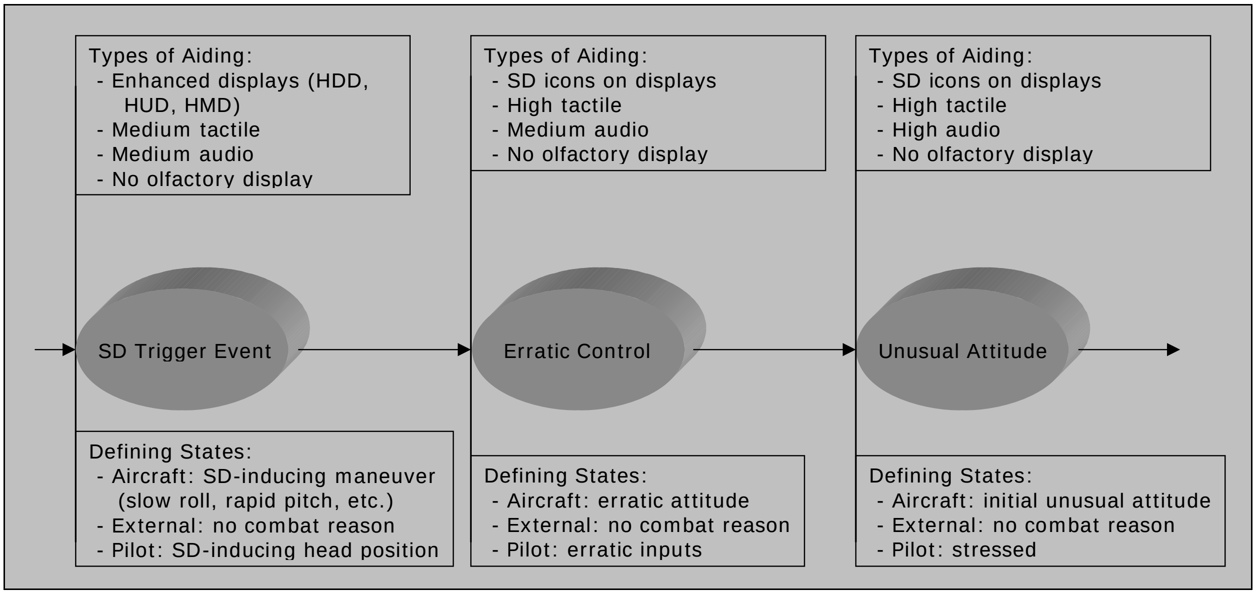

Figure 17. SD Evolving remediation network**.**

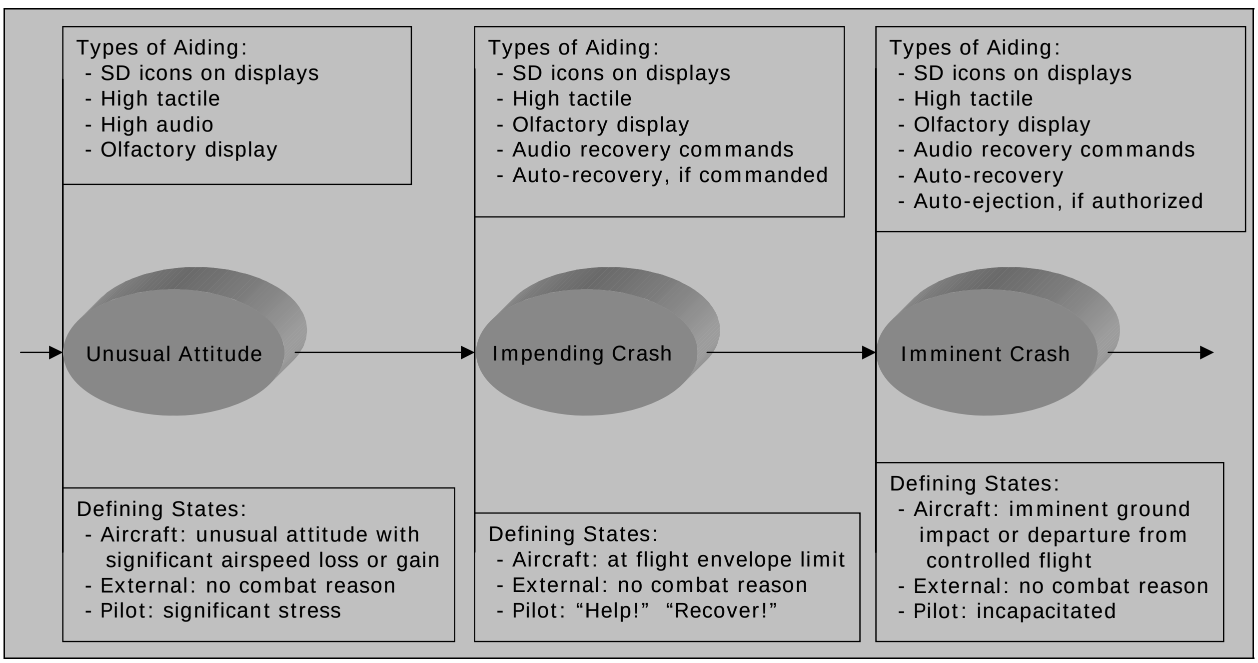

Figure 18. SD Critical remediation network.

As mentioned previously, we were unable to thoroughly test SOAS's countermeasure logic, since the emphasis in Phase II was necessarily on detection. Modeling pilot multisensory workload is non-trivial, as is assessing the true aircraft state and severity of the situation. The logic behind increasingly intrusive cues and countermeasures is compelling, but needs testing with naïve pilots.

The planned progression is to begin with a unique visual cue and aid, the SD Icon. As an SD situation worsens, SOAS would trigger an audio cue – a unique tone to signify "SD suspected."

If the situation continues to deteriorate, a tactile cue is next. For example, vibrating all of a tactile vest's tactors would presumably help get the pilots attention, with the implicit message again being "SD suspected; check attitude." A unique harmless olfactory cue (an aroma) was postulated as the next most intrusive. If cuing yields no improvement to the situation and the pilot has entered an unusual attitude that would result in a crash if not corrected, then active countermeasures begin. All the time, the unique SD Icon is displayed. Added to it are voice commands to return to straight and level flight. When auditory workload is high, tactile vest commands trigger. If the situation continues to worsen, a hypothetical auto-recovery system triggers (auto-GCAS is one such system, currently in use on the Swedish Grippen C). As a last resort, if the airplane does not recover (perhaps due to damage or a stall) a hypothetical auto-ejection could save the pilot's life. For civilian aircraft, there exists a ballistic recovery system (a parachute for the whole airplane) that would substitute for the above auto-recovery and auto-ejection countermeasures. The only other compensatory action triggered by SOAS (hypothetically) is another olfactory one – a smelling salts odor for use during Coriolis illusions to help the pilot "snap out of" any resulting incapacitation.

Developing and testing a SOAS that employed all the above cues and countermeasures are important next steps (Small & Bass, 2000), but exceeded the scope of Phase II as we emphasized getting the detection portion of SDAT/SOAS in satisfactory condition. As the reader can see from the above explanations, triggering the wrong cues or countermeasures or triggering them at the wrong time is worse than doing nothing in our view. That is why detection had to take priority.

3.3 Experimentation

We designed and conducted four experiments in Phase II (Figure 19); three were formal IRB-approved experiments; one was an informal flight test to generate data for the models, rather than to understand human performance per se. The flight test and a somatogyral experiment in the Air Force Academy's General Aviation Training (GAT) simulator supported the detection part of our work. An SD Icon experiment and a SOAS test (in the Academy's stationary F-16 simulator) supported the aiding portion of our research.

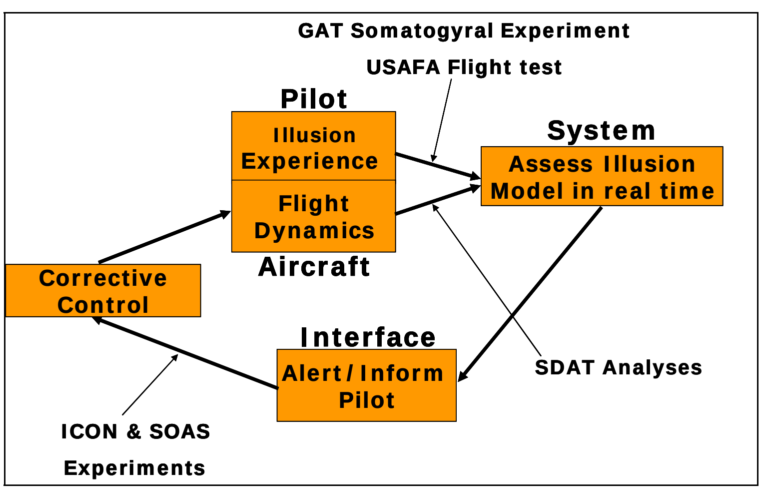

Figure 19. Rationale for Phase II experiments.

Detection Focused Experiments

The GAT motion-based simulator helped explore the somatogyral illusion in a controlled environment. Each trial spun volunteer cadets at one of three different speeds for one of three different durations (Figure 20). One goal was to fill some knowledge base gaps by obtaining quantified subjective perceptions of washout and illusory rotation for spins in a range that approximated fighter aircraft yaw axis (heading) rotation rates for normal turns, as well as accelerate Graveyard Spiral or Spin conditions.

The results helped us fine-tune our washout calculation (i.e., exponential decay time constant) and the perception of the magnitude of illusory rotations upon stopping the original actual rotation. For details, reader should see the ASEM manuscript in Appendix A.

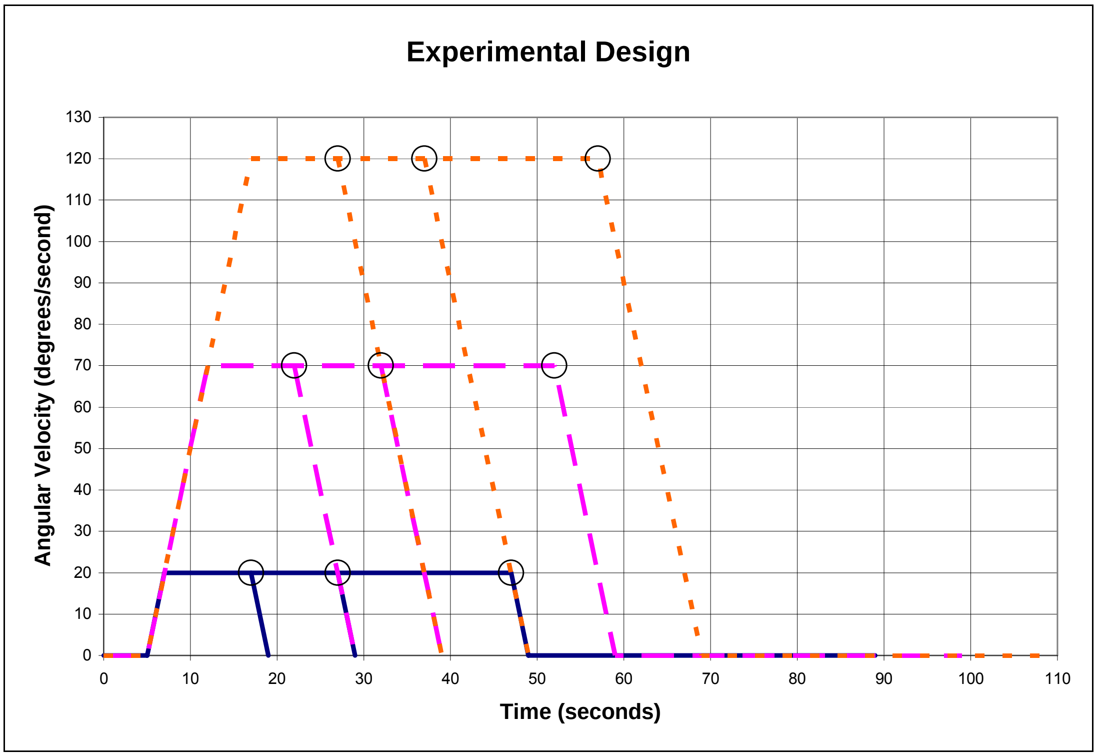

Figure 20. Spin plots for profiles at 20, 70, and 120 degrees/second for 10, 20, and 40 seconds with 10 degrees/second^2 ramp-up and ramp-down accelerations.

The goal of the flight test was to subject two volunteers (one female, one male) to the Leans and other SD-inducing maneuvers while recording their quantitative estimate of their perceptions of roll and pitch. The subjects were blind-folded while a safety pilot flew 10 different maneuvers. The subjective perception recording device operated flawlessly; unfortunately, the GPS-based flight data recorder did not. Therefore, it was difficult to perform a quantitative comparison and further validate or calibrate our SD models. The results of the informal flight test are in Table 2. Data from the female are in pink, and from the male in blue. Times are in seconds and angles in degrees. Maneuvers indicate a bank angle, direction, and time the bank was held. So "30L, 1 min" means a 30-degree bank was flown for a full minute. Results indicate inter-pilot, as well as within pilot variability. There was insufficient time to fully analyze the data, but none completely contradicted our modeling assumptions.

Table 2. Flight test collated data.

Maneuver Description	Times from end of maneuver to perceived S&L	Average Times	Perceived max bank angles	Average max perceived bank angle	Perceived max illusory bank angle	Average max illusory bank angle
30L, 1 min	15.8; 21.6	18.7	1.4; 23.5	12.5	14.7; 0.0	7.3
30R, 1 min	9.0; 6.2	7.6	1.7; 5.8	3.7	17.0; 21.6	19.3
45L, 1 min	0.0; 33.8	16.9	25.1; 54.4	39.7	0.0; 0.0	0.0
45R, 1 min	3.2; 9.4	6.3	10.9; 47.4	29.1	0.0; 11.2	5.6
30L sub-threshold, 1 min	0.0; 44.8	22.4	0.0; 10.6	5.3	9.8; 18.3	14.1
30R sub-threshold, 1 min	1.2; 28.4	14.8	0.0; 16.5	8.3	6.2; 7.3	6.7
30R, 10 sec; 30L, 10 sec	0.8; 3.2	2.0	31.5; 42.2	36.9	0.0; 30.6	15.3
30L, 10 sec; 30R, 10 sec	17.0; 10.4	13.7	21.6; 32.4	27.0	28.7; 31.2	29.9

We hope to have time during follow-on research to understand these data, and, even better, to re-do the test as a formal experiment with fully functioning aircraft state recording equipment. In addition to comparing actual flight data to subjective perceptions, we would like to flight test the efficacy of a more fully developed version of SOAS.

Aiding Focused Experiments

The first aiding focused experiments examined the usefulness of our innovative SD Icon on a desktop simulator. The second examined the value of the Icon and other non-visual countermeasures in a higher fidelity simulator using real fighter pilots, rather than Academy cadets. The first (Icon) experiment indicated that the Icon could be helpful as a command display to help pilots recover from unusual attitudes. Cadet volunteers were the subjects. Readers interested in details should see the first International Journal of Aviation Psychology (IJAP) manuscript, which has been accepted for publication, in Appendix A.

The second aiding experiment also presented subjects with sudden unusual attitudes. They flew recoveries using the baseline F-16 simulator displays, with Icon only aiding, and with Icon plus voice command aiding, or Icon plus tactile vest command aiding. Results proved the value of aiding over the baseline as there were significant improvements to initial response times and fewer roll reversal errors. In the worst unusual attitudes, the two conditions of multisensory aiding (Icon plus voice and Icon plus tactile) were significantly better than the two other conditions in terms of initial correct response times. Again, for more details readers should see the second IJAP draft manuscript (recently submitted) in Appendix A.

We used traditionally designed human factors experiments to support our modeling detection and aiding countermeasure hypotheses. The culmination of our dual approach to SD – detection and aiding – is a software product that is useful for *post hoc* accident data analyses and for eventual use as an *in situ* cockpit aid. The software is explained next.

3.4 Software Design & Development

Early in this project it was suggested that it would be very useful to have a software tool that allowed analysts and investigators to evaluate data sets from actual flights with the SD detection models. At the time, the team was using a software environment that supported development and testing of the code for the models. While the focus of the project was to work toward developing a cockpit system, creation of a desktop software package that both demonstrated the algorithms and supported actual analysis seemed like a very useful intermediate step. The result was the Spatial Disorientation Analysis Tool (SDAT).

SDAT is now a Windows-based desktop software package complete with User Guide and built-in Help documentation. The SDAT User Guide describes the functioning and use of the system in detail and is a separate deliverable under this contract. This section of the report will provide a brief summary of the functionality and interface in terms of how it supports the design and development efforts of the project. In addition, this section briefly describes the heuristic usability analysis that was performed on the SDAT interface, and the patent application for the system in general.

Figure 21 shows where SDAT fits within the combined SD detection and pilot aiding methodology. The tool includes all the SD model algorithms for perceived attitude prediction and disorientation illusion sequences as described in Section 3.1 of this document. In addition, it includes a demonstration of how the countermeasures of the aiding system would execute to support the pilot once the system predicts that an SD illusion is likely to be occurring. Users of the software can load flight data files as specifically formatted Excel spreadsheets. When an analysis of the file is executed, both the detection and aiding algorithms evaluate the data line by line and provide results dynamically in real-time or faster. While the analysis tool could have been designed to provide a single set of results following tool execution, the process of line by line analysis and results more closely represents how the system would function within a cockpit. The detection system would evaluate aircraft motions and other inputs as they occur and the aiding system would present appropriate and perhaps changing levels of countermeasures as necessary. Many of the set-up and execution setting options in the tool reflect the potential use of the algorithms as part of a dynamic cockpit system.

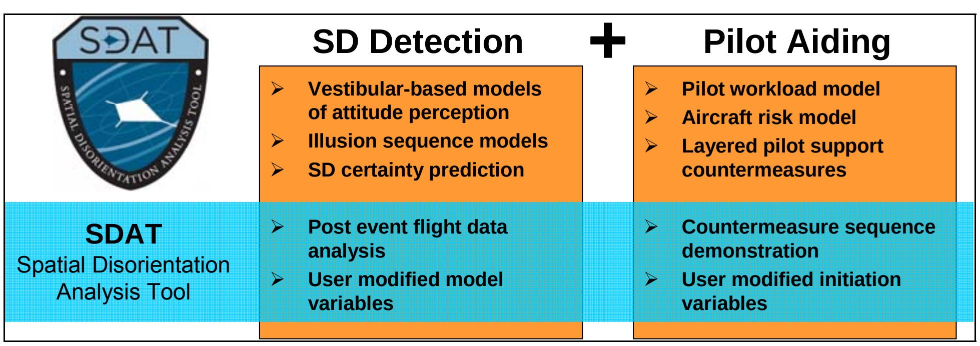

Figure 21. Detection and Aiding as implemented in SDAT.

SDAT Detection Analysis

SDAT extends the SD detection capability into the realm of analysis by allowing the users to modify both perception prediction and illusion model values and providing a range of dynamically displayed results. Figure 22 shows the initial screen display when SDAT is executed. The interface is a standard Windows design with pull down menu options and a toolbar. The main area of the window consists of a two-layer tabbed interface that allows the user to set initial conditions for analysis and view various results options. The following are short summaries of each of the options.

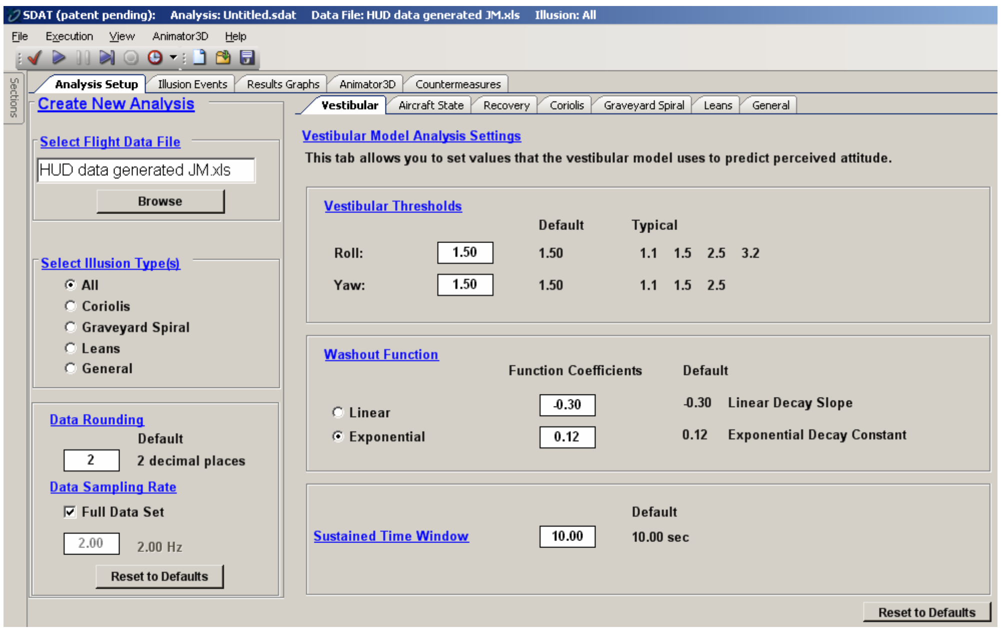

Figure 22. SDAT initial setup screen.

The following are short summaries of each of the options including their purpose and some of the reasoning behind their functionality. For complete details on the use of the tool, see the SDAT User Guide.

Flight Data File – the tool allows the user to select a file to analyze that contains the flight data. Files must be in Excel with appropriately formatted columns of flight dynamics data. The flight data used by the tool could also be available to an SD cockpit detection and aiding system during flight.

Illusion Type – The interface lists all the types of SD illusions currently included in the detection system. The General Illusion simply looks for specified deltas in actual versus perceived values for yaw and roll rates and pitch angles. The tool allows the user to evaluate a flight data set for each individual illusion type or for all of them at the same time. The 'All' option more closely represents how the detection system would function within a cockpit.

Data Rounding and Sampling Rate – Some of the flight dynamics data sets that we received (or created using X-Plane, a desktop flight simulator) have sampling rates of greater than 8 Hz and values to 10 significant digits. For the purposes of modeling human perception, it is not necessary to have this level of precision within the data. Changes to aircraft attitude values beyond 10ths or 100ths of degrees are not perceptible by humans. Likewise, variations near the 1/10 of a second range can relate more to aircraft vibration than actual attitude changes. As such, the tool allows the user to set both data rounding values and a sampling rate that better correspond to human perceptions. This capability filters some of the noise in the attitude data and focuses the calculations on changes significant to human perception.

Vestibular Thresholds – As described in the section on SD related physiology (Section 2.3) various research efforts have found different values for vestibular detection thresholds. Indeed, thresholds may vary across individuals or circumstances. The tool allows the user to set specific threshold values for use in the semi-circular canal perception model for both roll and yaw.

Washout Function – The tool supports both linear and exponential decay functions to simulate the effects of vestibular washout. Functional coefficients can also be set by the user to modify the decay rate of the linear function and the shape of the curve for the exponential function. The default value of 0.12 for the exponential function reflects the rotation perception decay results of the somatogyral experiment (Section 3.2).

Sustained Time Window – This setting refers to the Mulder's Law implementation (section 3.1) for prolonged acceleration detection. User can set the range of time used by the Mulder's calculation to check for perception of combinations of otherwise sub-threshold instantaneous rotational acceleration values.

In addition to the initial set-up window, there are windows for the individual SD illusions that we modeled: Leans, Graveyard Spiral, and Coriolis. Those illusion sequence descriptions are next.

Illusion Sequence Model Settings

Because there is still some uncertainty about quantifying misperceptions and recognizing that there is variability between pilots as well as within individual pilots under varying circumstances, the tool enables the user to alter values for each of the three illusion models described in Section 3.1 (and the General Illusion) to vary the analytical parameters. Figure 2323 shows the initial settings interface for the Leans model (see also Figure 12). The basic version looks for sub-threshold roll actions starting from straight and level flight (Event 1). The user might choose to search for a Leans sequence that initiates from a greater initial roll angle or rate by changing the values for Event 1. In addition, the level of certainty can be varied for each different event in the sequence. Likewise, values for the other three events can be modified. In a similar way, settings for Coriolis, Graveyard Spiral and the General Illusions can be changed. In this manner, the tool supports a sensitivity analysis across a range of detection settings.

SDAT outputs include a whole range of analysis support capabilities. The final results of any analysis include time-stamped detection settings and values in tab-delimited text files. These files can be opened for further analysis or presentation in any software package that supports data in spreadsheet formats. The tool also uses several different types of displays to present detection results dynamically during analysis execution. These include the timing of the execution for each event in each illusion sequence, a graphing window for a range of flight data and results values, and a window for the dynamic rendering of actual (blue) versus perceived (red) aircraft attitude (Figure 24).

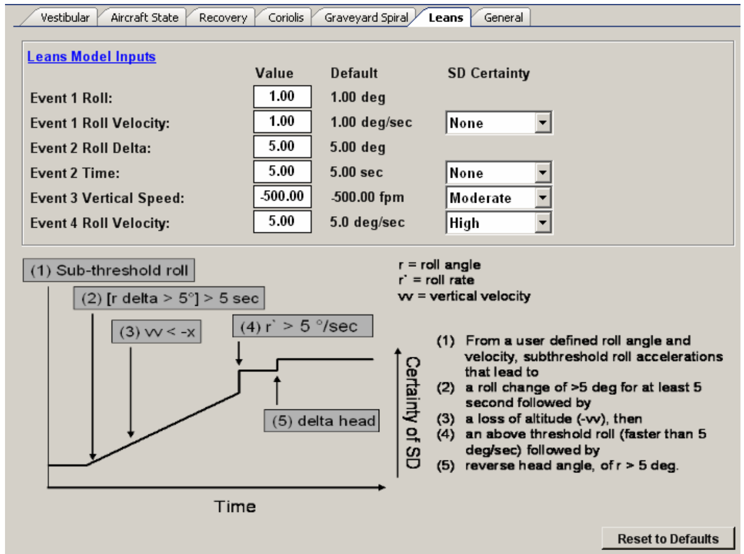

Figure 23. Leans model settings screen.

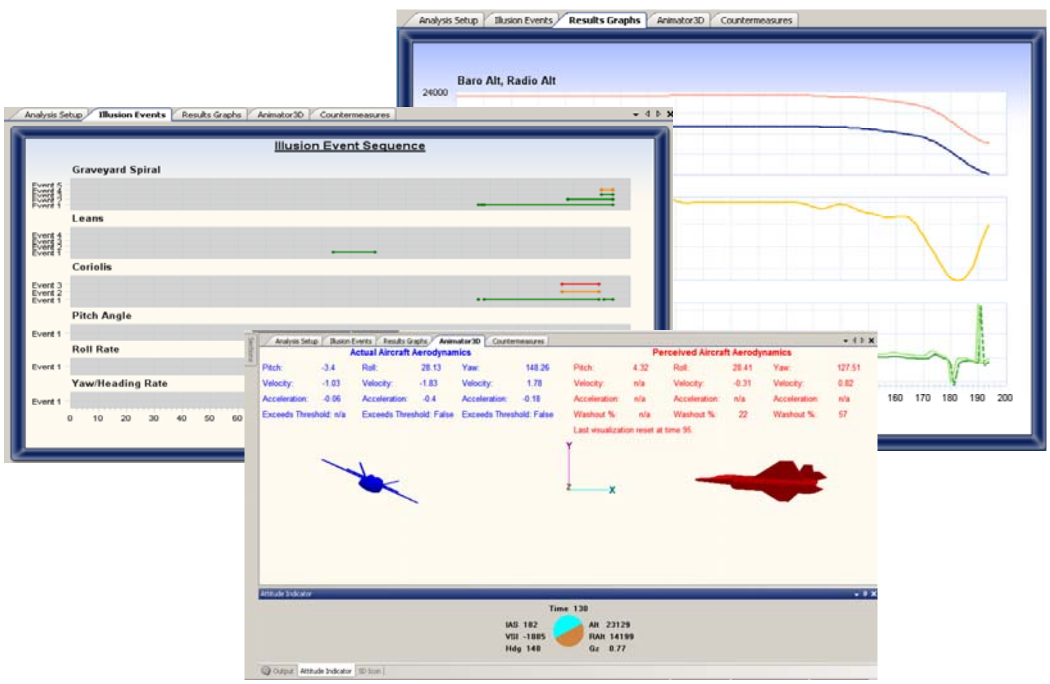

Figure 24. Example SDAT dynamic analysis screens.

SDAT Aiding Demonstration

In addition to the analysis capabilities of the detection system, SDAT includes the algorithms developed for the pilot aiding portion of the system (as explained in Section 3.2). During an analysis, the tool presents the changing levels of countermeasures that the aiding system would use in response to different levels of disorientation and aircraft risk (i.e., consequence severity). While not strictly necessary for the purpose of analyses, this capability enables demonstrating the complete SD detection and pilot aiding system.

Figure 25 shows the countermeasure initiation demonstration screen. The left side shows which illusion(s) and SD certainty levels are predicted by the detection system. The right side shows all the countermeasures described in Section 3.2. As the situation changes the output shows which countermeasures would be triggered in the cockpit to aid the pilot. This screen shot shows that under the current situation of a general yaw velocity illusion, the cockpit aiding system would be using the icon, audio and tactile command countermeasures to help the pilot recover.

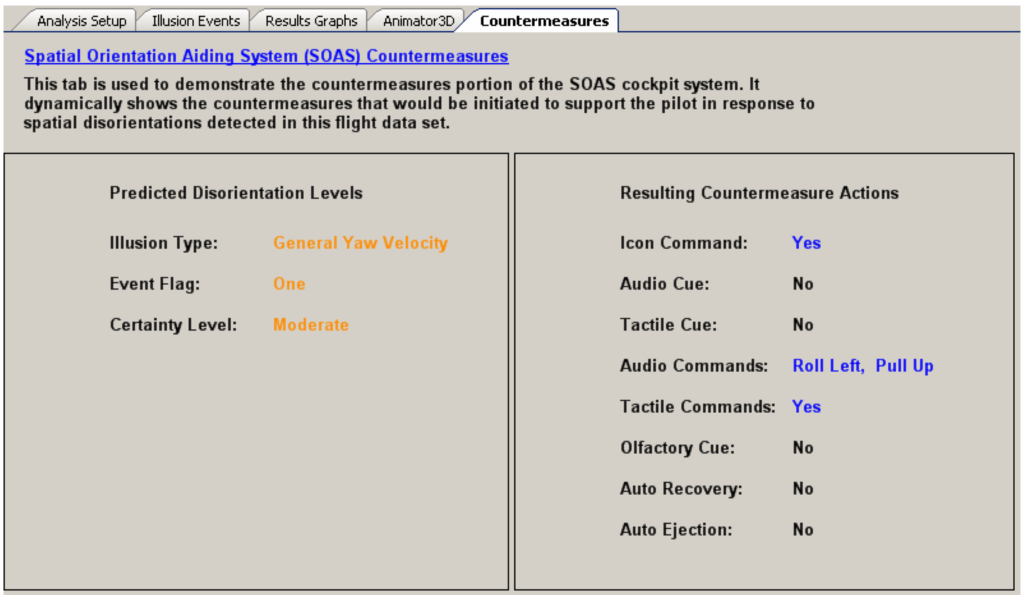

Figure 25. Countermeasure initiation demonstration screen.

In the same way that the tool allows users to modify illusion model settings, various algorithms related to the countermeasures can also be modified. In addition to demonstration, this allows for the testing of the sequence and timing of countermeasure initiation during flight data sequences. As an example of this capability, Figure 26 shows a screen shot of recovery code settings.

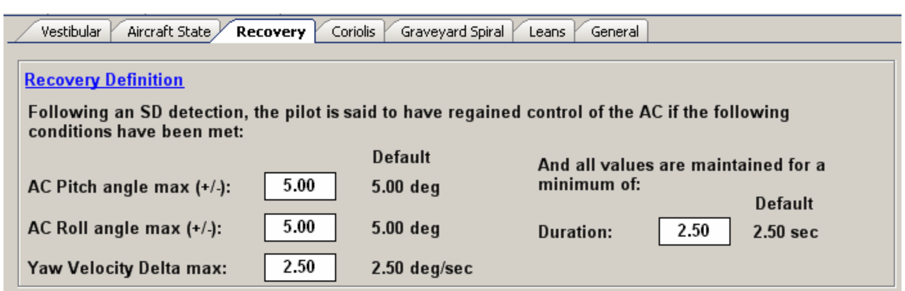

Figure 26. Recovery code user input screen.

In addition to the Recovery Definition, the tool includes options for modifying algorithm values for the Unusual Attitude Definition, Time to Impact Definition, and Perceived Attitude Angle Reset Definition. Each of these algorithms would be a functional part of any cockpit aiding system. The following are short summaries of how each of these algorithms interacts with both the detection and aiding systems.

Recovery Definition – Once the detection system has determined that an SD situation may be occurring and countermeasures have been activated, the system needs a way to determine if the pilot has regained control of the aircraft and recovered. The definition requires that the aircraft pitch and roll angles, and calculated yaw velocity delta are within specified values and that these values are maintained for a specified period of time. Once the system has determined that the pilot has regained control, all countermeasures and illusion event flags are turned off.

Unusual Attitude Definition – A detected SD situation may not necessarily represent a loss of aircraft control. Following an SD detection, if an unusual attitude is also detected, the system will increase the level of countermeasure intrusiveness assuming that the pilot is losing control due to the disorientation.

Impact Definition – The impact definition is used by the aiding system to determine when to initiate either the auto-recovery or auto-eject countermeasures. Altering the time to impact values allows the user to set the countermeasure triggers as desired.

Perceived Attitude Angle Reset Definition – The purpose of this algorithm is to reset the displayed perceived attitude angles of pitch, roll and yaw to the actual aircraft values in the 3D Animator window. The reset does not affect the perceived angular velocities or any other values or operations within the detection system. The reasoning is that the perceived attitude calculations are limited in that there are many other physiological inputs to sense actual orientation. While the yaw and roll rate perceptions are well represented, the resulting attitude angles are not. As such, that algorithm takes advantage of long periods of straight and level flight in a data set and low perception delta values to reset the perceived angle values being displayed.

Heuristic Usability Analysis

The development and current use of SDAT has been primarily by the same group of people. So, it was difficult to determine what sorts of usability problems the software design might contain. In an effort to increase the ease of use and understanding of the tool for future user groups, a heuristic usability analysis was performed on the interface as part of our design and development.

Heuristic analysis is a form of usability evaluation commonly used during software design. The process was invented by a Nielsen (1994) and requires the use of interface design experts rather than users. Sometimes called ‘discount usability’ the process will not find all the usability problems but is less expensive than formalized usability testing. We used three in-house human factors engineers who were experienced with performing heuristic evaluations but who had no part in the design or development of SDAT. They each performed independent evaluations using a list of common interface design ‘rules of thumb’ (heuristics). They then combined their individual analyses into a single report that prioritized the problems they found. The list of heuristics and their analytical results are in Appendix B.

The results of the analysis proved very useful to the design team. Due to timing and funding limitations, though, we were only able to implement a few of the changes recommended by the evaluators. We focused on issues that were listed as serious and were also able to implement some of the quicker changes. A more complete implementation of the heuristic team’s recommendations will have to wait for further funding.

Patent

Because of the innovative nature of our approach and its embodiment in the SDAT/SOAS software, we applied for a US patent. We filed a provisional patent application (PPA) on May 6, 2005 and the final application on August 15 (Appendix C). We have yet to receive feedback from the Patent and Trademark Office (PTO), other than their acknowledgment that they received our application (Appendix D).

We began researching the feasibility and benefits of patenting our SD tools at the suggestion of Bill Ercoline, with the subsequent concurrence of our technical customers and their contracting staff. We selected the Kansas City-based legal firm Lathrop & Gage, L.C. to serve as counsel. Not only does the firm has an established and highly respected intellectual property practice group, but a number of its most experienced attorneys work out of the Boulder office.

We were motivated to file a PPA before publicly disclosing our tools at the Aerospace Medical Association conference in May 2005 where we had an exhibit. Filing a PPA accomplished several things. First, it provided us with an official filing date that allowed us to publicly disclose the invention without jeopardizing our domestic or foreign filing rights. This is especially important for foreign filing, since most countries do not offer a one-year grace period for filing after public disclosure as does the US. It also prevented our own public disclosures from being used as “prior art” against us. Finally, it placed the burden on potential competitors to demonstrate proof of concept prior to our filing date.

Our strategy for the PPA (and consequently the regular patent application) was to claim the broadest range of concepts and methodologies possible. We began by widening the scope of our invention to support SD countermeasures and analysis in any context, not just aviation. With this thinking, our tool could conceivably be used to assist disoriented divers, firefighters, astronauts, or anyone else who is regularly exposed to conditions conducive to vestibular SD illusions. Additionally, we avoided mention of specific platforms and computer programs used to build our tool. A generalized description of how the tool was constructed lays claim to all its possible manifestations and thereby prevents competitors from building essentially the same device with insignificant differences.

Due to funding limitations, we elected to not file a Patent Cooperation Treaty (PCT) application to initiate the foreign filing process; foreign patent applications are very expensive. A PCT application is *not* a patent application. Rather, it is a form of international registration for an invention that allows the inventor(s) to research the feasibility and benefits of obtaining patent rights in foreign countries before making a significant commitment of time and money. The US application cost $15,000; each foreign filing costs about half of that of the US filing, not counting language translation services.

3.5 Accident Data Analyses

During the early development of both the detection and aiding algorithms, we used flight data sets generated from a desktop flight simulator (X-Plane). The scenarios were flown by project personnel to carefully recreate the specific illusions and sequences we were trying to detect. The sequences were often followed by periods of erratic movement to simulate a loss of control. Finally, we often flew recoveries to simulate a pilot's response to supporting countermeasures. These data sets proved very useful. The flight simulator could output all the flight dynamics data we needed and the sequences allowed us to debug our detection and aiding algorithms as coded in SDAT. However, since the sequences were developed specifically to work with our models, we were uncertain how well the algorithms would perform with data sets from real flights.

We were very fortunate to obtain 12 such data sets from actual SD mishaps. The Air Force Safety Center (AFSC), Navy Aeromedical Research Lab (NAMRL), and National Transportation Safety Board (NTSB) were all extremely supportive of our efforts and were gracious enough to share not only flight data sets from investigated mishaps but also the associated safety board investigatory findings. These data sets and the ability to evaluate the conclusions from SDAT proved invaluable to this project. We are indebted to our colleagues from each of these organizations and look forward to continuing to work with each of them.

Each of these data sets was from an actual SD incident that had been previously investigated. It was agreed that our use of the data was for our own development purposes and that none of our results would be used to modify the conclusions from any of the investigations. In addition, the use of the AFSC data sets required us to sign a non-disclosure agreement; so, there will be no discussion of those data sets in this report. In addition to aiding us with our system development, we created analysis reports for each data set containing the results from SDAT. These reports were provided to each organization who gave us data sets. The remainder of this section includes summaries of four of these analyses. Unless otherwise controlled, the complete text of these analyses is available upon request. It should also be noted that none of these data sets included head position values for the pilot. As such, the Coriolis model was not used as part of any of these analyses.

In addition to receiving actual flight data sets, we created one flight data set from a video recording of a HUD during an apparent disorientation. The following SDAT summaries include two data sets from the NTSB, one from the Navy, and the recreated HUD tape sequence. In each case, the basic event sequence is described and the main SDAT findings are presented along with a comparison of the conclusions from each investigation for the NTSB and Navy data sets. Also, we discuss how the analysis of each data set supported our development process. We conclude with our detection score for all 12 data sets. Each SDAT analysis was initially performed independent of the official findings in order to be a "blind" test of SDAT. Following each analysis we compared the SDAT results with the conclusions of the incident investigators.

Consequently, these comparisons function as a basic validation of the SD detection capabilities of our system.

NTSB Data Set 1: Strasburg

During a night flight in bad weather, this King Air 200 lost electrical power. Just over 2 minutes later during a long right turn, it spiraled into the ground killing all aboard (NTSB, 2003). Figure 27 shows graphs of aircraft altitude, roll angle, yaw rate and perceived yaw rate. SDAT detected a Leans illusion sequence with the sub-threshold roll resulting in over 10 deg of roll change starting around time 90 and extending for approximately 20 seconds. SDAT also detected a yaw rotation washout with an increasing perception delta reaching at least 10 deg/sec followed by the apparent loss of control.

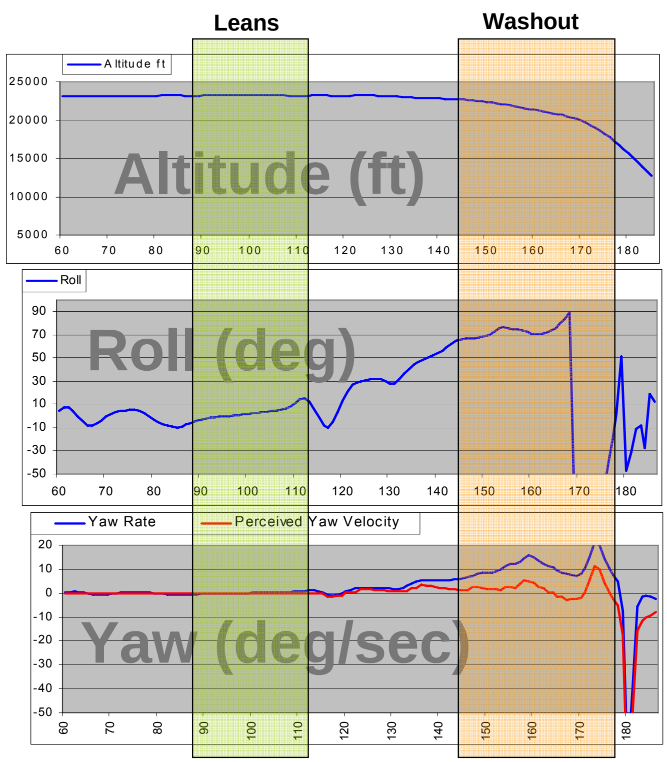

Figure 27. SDAT Leans & Washout detections with graphs of altitude, roll angle and yaw rate.

The comparison with the NTSB results showed that the detected Leans sequence started just after the loss of electrical power (Figure 28). The yaw washout detection coincided with the increasing final spiral. The NTSB concluded that a Graveyard Spiral illusion contributed to this fatal accident.

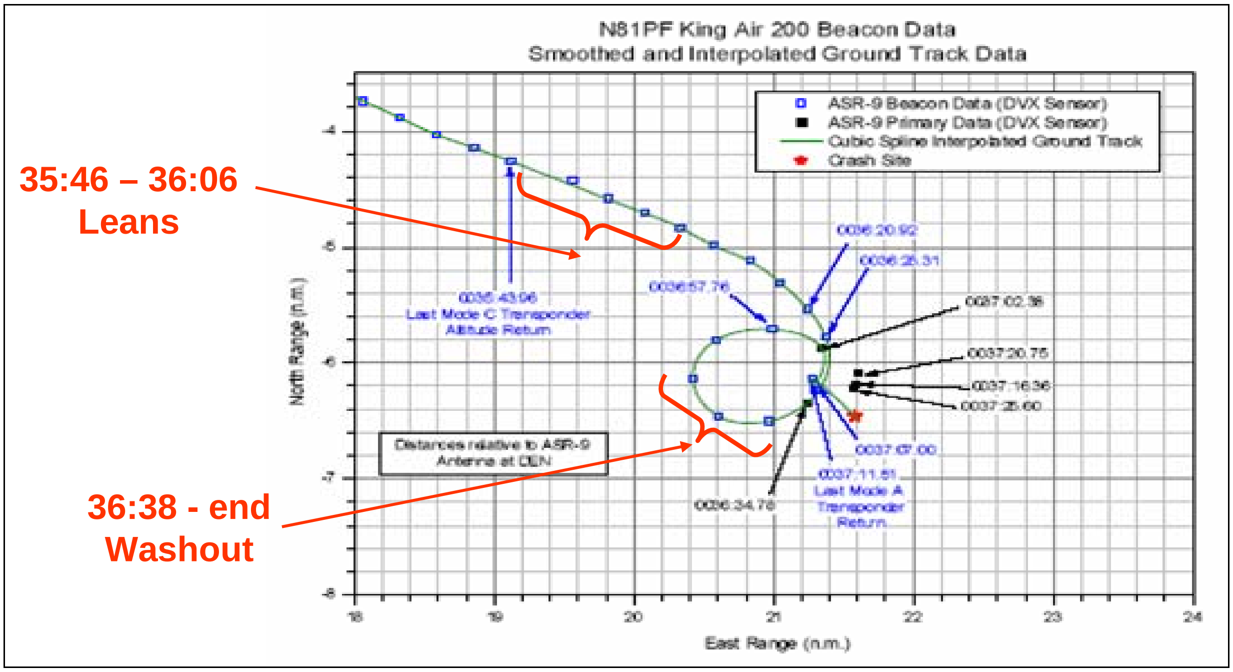

Figure 28. NTSB ground track and events timeline combined with SDAT findings.

The model of the Graveyard Spiral illusion includes three turning events rather than the single one that occurred here. While the current detection system calculates the resulting yaw rate perception delta, future versions of the Graveyard Spiral model may need to include a sub-threshold beginning to an increasing yaw washout event.

NTSB Data Set 2: Hillsboro

During a night flight in bad weather, the airplane carrying Governor Carnahan lost the primary attitude indicator shortly after takeoff. After nearly 10 minutes of working with an air traffic controller (ATC) and reporting attitude difficulties, the pilot apparently lost control and crashed (NTSB, 2002). Figure 29 shows the actual yaw rate and the calculated perceived yaw rate. SDAT detected two instances of yaw rotation washout resulting in perception deltas of over 3 deg/sec, the second of which occurred just prior to the apparent loss of control.

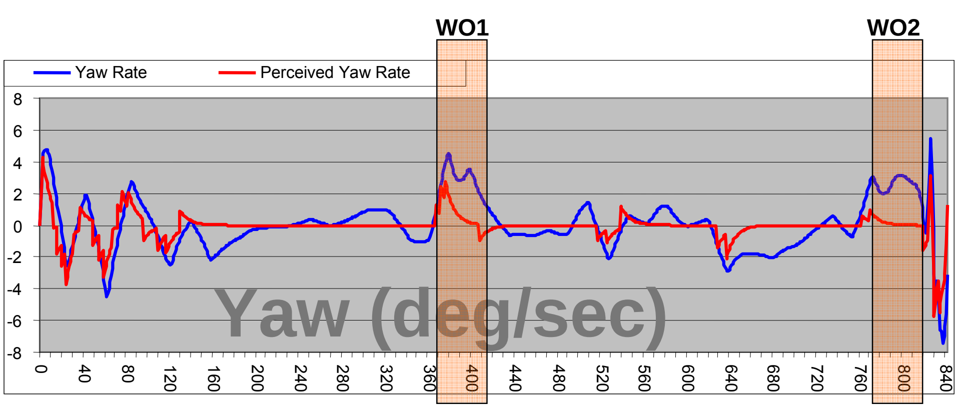

Figure 29. Actual and perceived yaw rate with detected washout events.

Figure 30 shows the ground track and communication timeline of the flight. In addition to the two instances of washout, SDAT detected three Leans sequences. Each are associated with the three major turns taken during the last half of the flight sequence. The comparison with the NTSB findings showed that the first and third turns were directed by ATC. As such, it is unlikely that the two Leans sequences associated with these turns were an issue as they were intentionally initiated. However, the second Leans sequence coincides with a turn that apparently was not directed by ATC and may have been due to SD. Finally, the NTSB concluded that a Coriolis illusion may have contributed to the final apparent loss of control as the pilot may have been trying to look across the cockpit to use the secondary attitude indicator. The washout detected during the last turn is consistent with an initiating event of the Coriolis illusion.

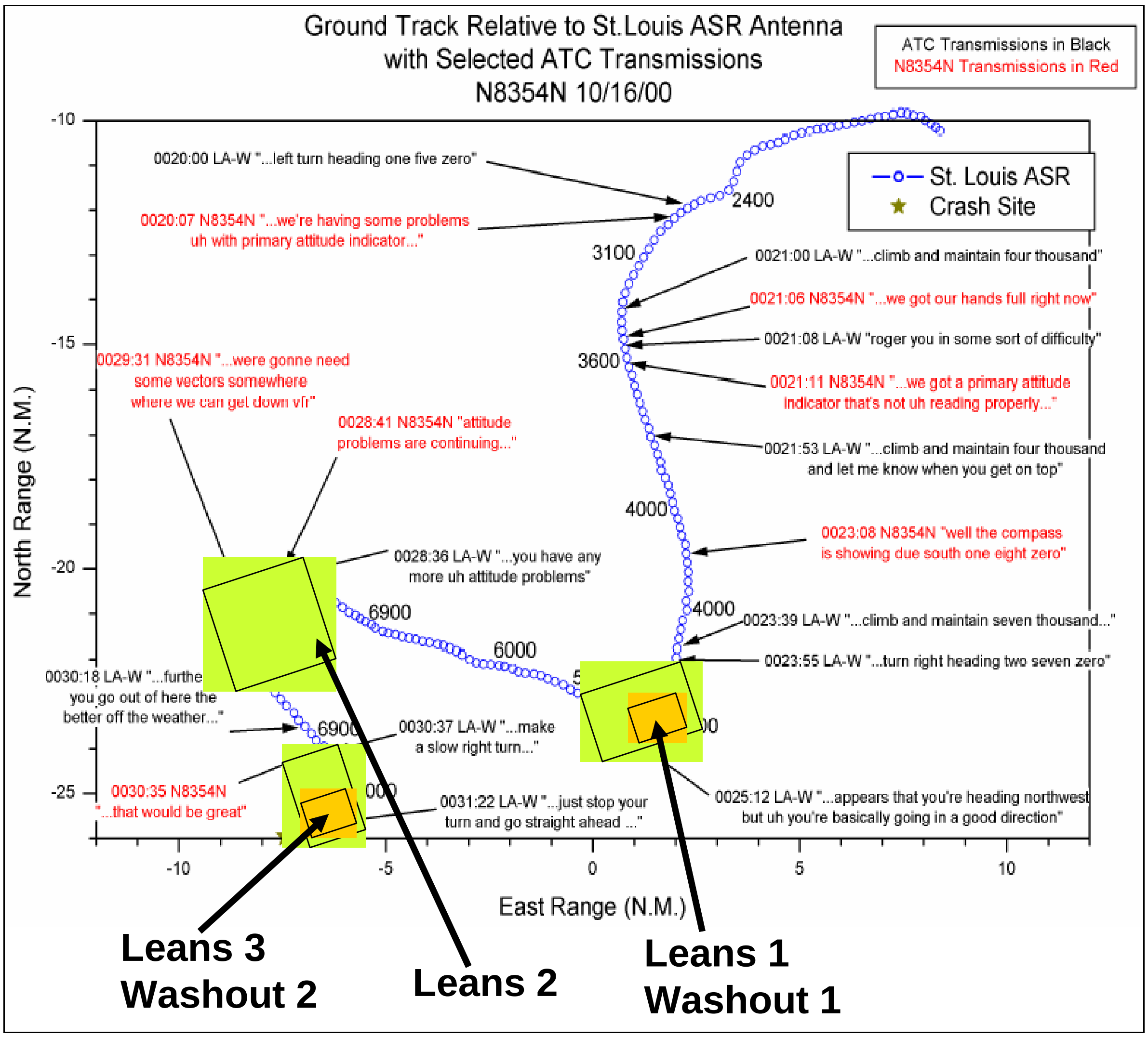

Figure 30. NTSB ground track and event timeline with SDAT detections.

Navy Data Set

This data set was received with almost no background information. Based on the actual yaw rate graph in Figure 31, the aircraft was in a long left turn, briefly stopped turning, and then continued back into the left turn with a heading change rate of up to 5 deg/sec. SDAT did not detect any Leans or Graveyard Spiral illusion sequences. However, it calculated that nearly all the turn accelerations were below the vestibular threshold, so that the pilot would sense almost none of the turn as shown by the red line of the graph.

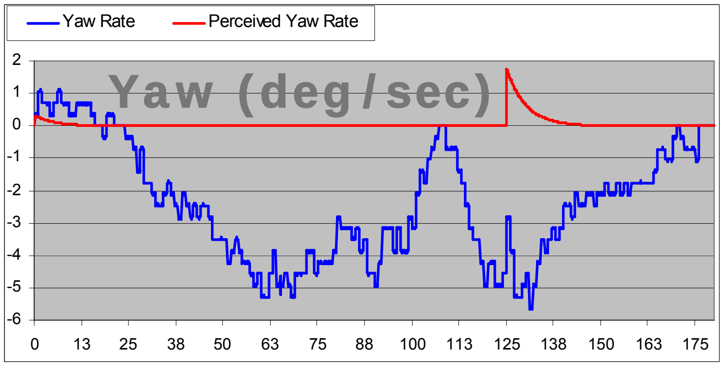

Figure 31. Actual and perceived yaw rates.

Continuing our analysis, SDAT calculated a steadily increasing pitch angle perception delta near the end of the data set. Figure 32 shows altitude, airspeed, and pitch angle for the flight as well as perceived pitch angle and the two periods of pitch angle perception delta. As airspeed increases while climbing, starting from time 125, the perceived pitch increases. The pilot either does not feel the actual decrease in pitch over the next 20 seconds or is intentionally responding to the perception of increasing pitch up by pushing the nose down. The process accelerates as airspeed increases due to the loss in altitude starting at about time 165. These findings coincide with the Navy's conclusion of a pitch perception problem.

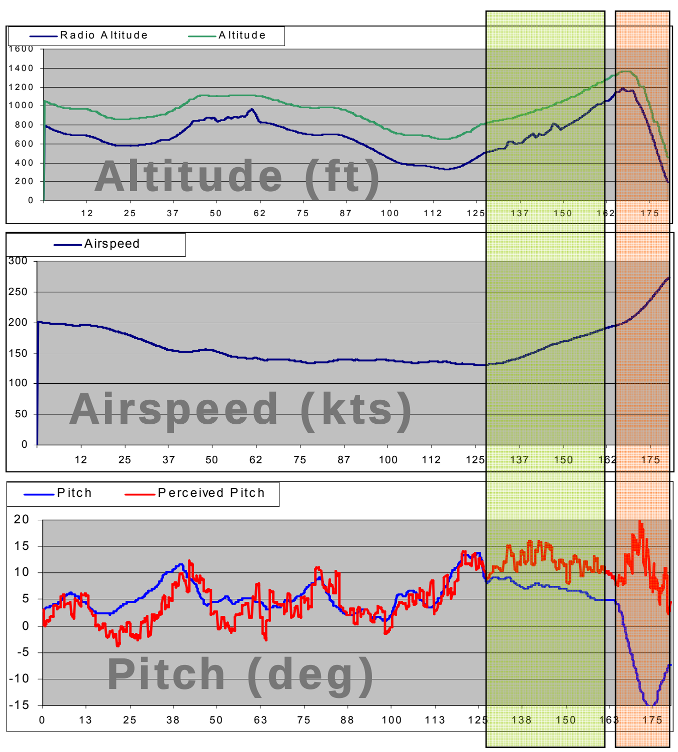

Figure 32. Altitude, airspeed and pitch angle graphs with pitch perception deltas.

The analysis of this data set was useful in two ways. First, it confirmed that our developing analysis process was effective. Although we were initially focused on the sub-threshold yaw accelerations, the completion of the detection process allowed us to find the pitch perception problem related directly to a somatogravic illusion. Second, it confirmed that our pitch perception model was functioning well, but highlighted the need for a pitch-based illusion model as part of the SD detection system.

HUD Recording Data Set

The recording of this HUD tape was made available to us with no information about the context of the flight other than it occurred at night and might have included the use of night vision goggles. From an SD standpoint, it is compelling because the audio content shows that the pilot is aware of his disorientation and is eventually able to recover. We used video editing software to slice the first 70 seconds into 1 Hz segments. We obtained most of the necessary flight dynamics data from values on the HUD (Figure 33). For pitch and roll we used a graphics program to measure angles relative to a horizontal reference line inserted into each image (Figure 34).

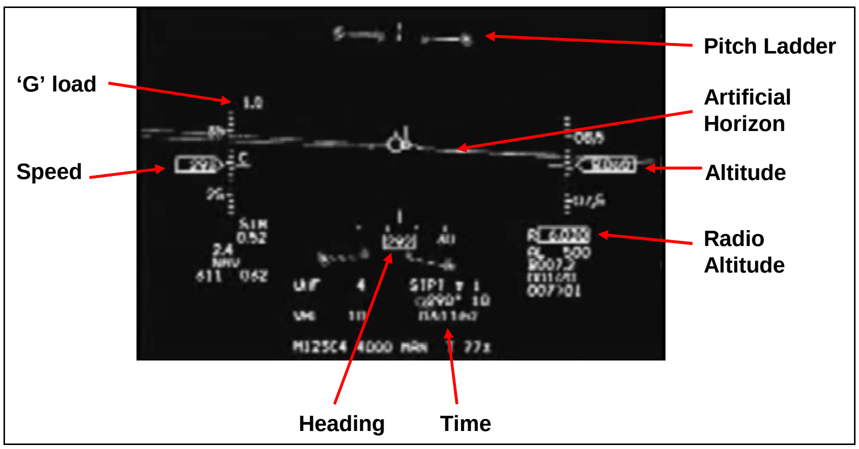

Figure 33. Flight data value locations on the HUD tape recording.

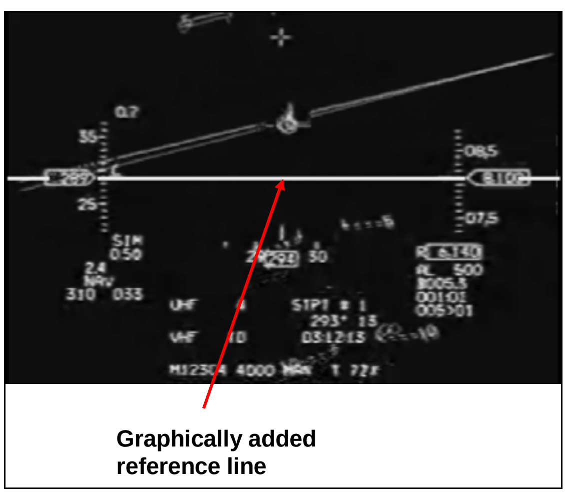

Figure 34. Technique of obtaining pitch and roll angles from the HUD tape.

Figure 35 shows the graph of the dramatic rolling action that occurred during the flight sequence. Included is a subset of the audio as transcribed from the recording. F2 is flying in the wing position relative to lead aircraft F1. F1 requests approach vectors to split F2 from the formation in preparation for landing (our assumption from the audio and our flight experiences). During this communication, F2 begins to experience increasing roll oscillations. His first expletive at time 25 seconds seems to indicate that he is aware of some sort of problem. Following an initial roll inversion, he calls "Lost wingman." and follows with another expletive as the roll inversions continue. He responds to a position request from the flight leader indicating his awareness of his disorientation. Approximately six seconds after the flight lead helps to focus the F2 pilot on the primary attitude indicator, he regains control of the aircraft and seems to proceed without further incident.

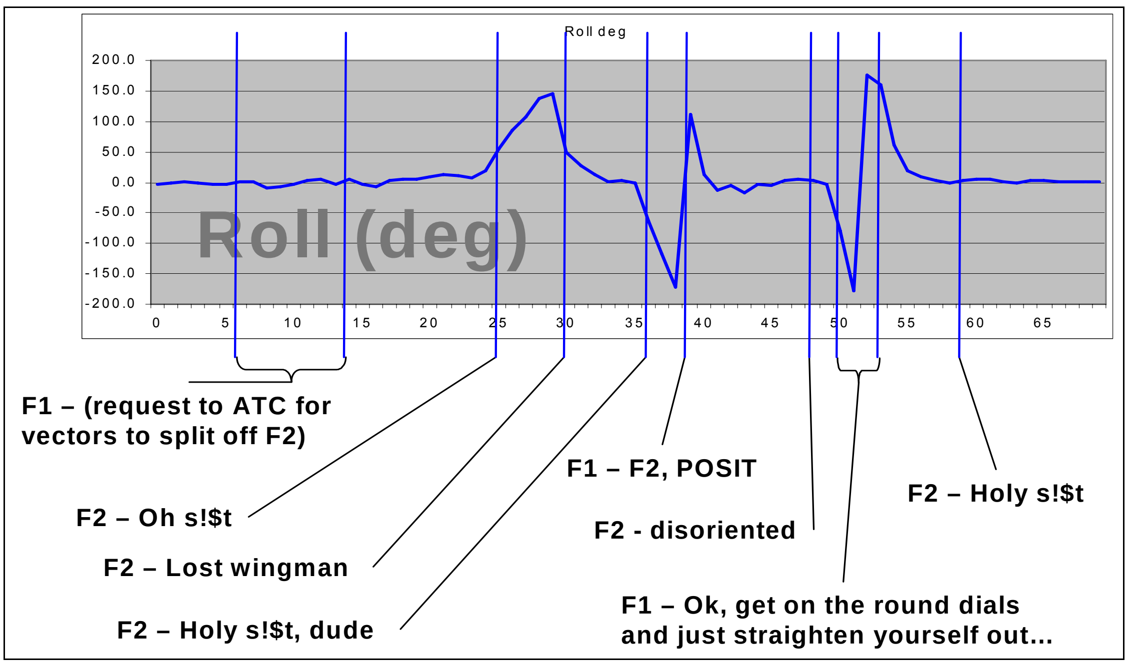

Figure 35. Roll angle sequence with subset of audio transcript.

Given the apparent roll control problems, we expected to find some sort of Leans illusion issue somewhere between 5 and 25 seconds into the flight sequence. SDAT, however, did not find illusion sequences of any kind; it found that most of the rolling actions were supra-threshold. Indeed, as the roll rate data for the first 25 seconds of the sequence shows (Figure 36), the only sub-threshold change occurs for about three seconds starting at time 19 seconds. While the result is a roll rate perception delta of about 3 to 4 deg/sec, it seems very unlikely that such a relatively small value alone could account for the subsequent events -- the multiple roll inversions.

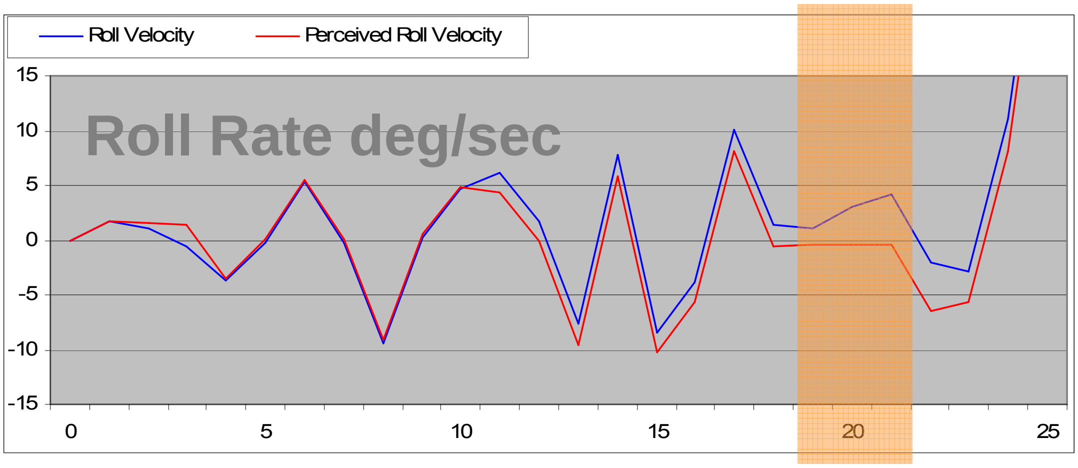

Figure 36. Actual and perceived roll rate and small perception delta.

A presentation and discussion of these findings surprised a number of other SD researchers familiar with this HUD tape sequence and indicated to them that the disorientation and apparent control problems may have resulted from something other than a vestibular-based perception issue alone, such as visual motion confusion of the inside-out representation of attitude on the HUD (Previc and Ercoline, 1999). Our use of this data set demonstrates the capability of generating flight data from a source other than a flight data recorder. It is possible, though, that our process for creating the data set may have introduced small errors to the angular rotation values. In any case, it demonstrates how a tool such as SDAT can be useful during an overall analysis of a flight sequence incident. The recording also demonstrates how an audio command, as performed by the flight lead in this case, can function as a very effective countermeasure.

Analysis Comparison Summary

Figure 37 shows the summary score of SDAT results as compared with the investigation results for each of the 12 data sets we analyzed during this project. The two NTSB and one Navy data set were each good matches. The HUD tape data set was somewhat inconclusive and is hard to evaluate without additional information. Of the 8 data sets provided by AFSC, we had a good positive match for one of them. For two of them we had good negative matches; that is, SDAT did not find any vestibular SD problems and the investigators concluded that visual illusions, not vestibular illusions, contributed to the mishaps. In the two cases where SDAT results did not match the investigators findings at all, further information showed that the use of our vestibular-based SD illusion models was inappropriate because of circumstances that point to non-vestibular illusions. In another two cases, the comparison is inconclusive. While both the investigators and SDAT indicate there were SD issues, there is no clear match. Finally, we were unable to complete the analysis of one of the data sets as it appeared to be corrupted (marked "N/A" in Figure 37).

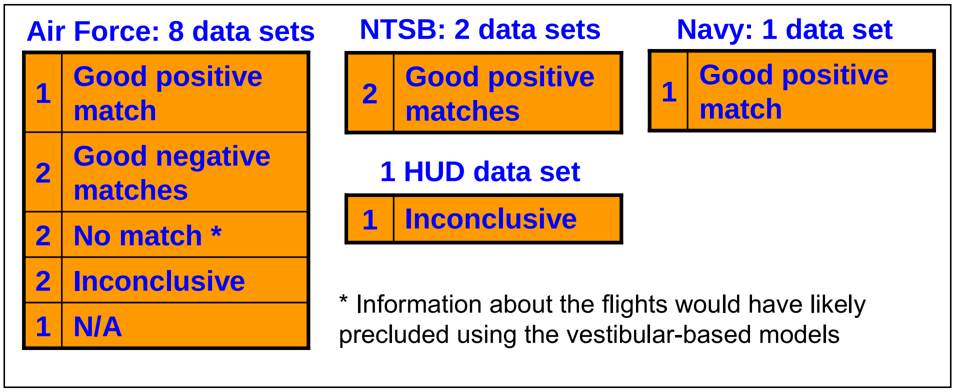

Figure 37. SD flight data analysis comparison results.

Based on these results, we conclude that our SD detection system in the form of an analysis tool is effective at finding vestibular-based perception problems in real flight data.

4 Recommendations for Future Research

As with most projects, the momentum for the accomplishments we would like to achieve exceeded the time and funding that we had to complete them. With this in mind, we have surveyed the items that we were either unable to complete or should be considered for future research and design efforts. The list is divided into the following subject areas:

- Improvements to the Detection System
- Improvements to the Aiding System
- SOAS Detection and Aiding System Testing and Integration
- Spatial Disorientation Research
- SDAT Software Enhancements
- Applications to Other Topic Areas

Each focus area and topic includes a short description of the potential future work and the reasons we feel it is needed. This list can be used for future proposals as additional funding and support becomes available.

4.1 Improvements to the Detection System

The SD detection system has proven its ability to detect a number of SD situations. However, there are a number of improvements that can be done to increase both the depth and breadth of detection capabilities. If the system is eventually to function within an integrated cockpit environment, these types of enhancements should be considered a required step.

Integration of Perception Calculations

The calculations for the perception of angular rotation and angle perception used in the current version of the detection system are functionally isolated from each other. They have proven effective in predicting portions of attitude perception. However, our vestibular system integrates orientation inputs from several sources at once to calculate overall attitude perception. We will need to determine how important each additional input is and if it affects the SD detection capability. Two specific cases are likely to be important future enhancements:

- The perception of bank angle can be represented by an integration of roll rate perception and applied G forces as they affect the proprioceptive system.
- In addition to the loss of the sense of rotation caused by washout during a continuous turn, the pilot may also lose the feeling of the bank angle associated with the turn. The result is the feeling of straight-and-level flight while still banked and turning. Combining the rotational washout calculation with the bank angle perception calculation will be needed to accurately reflect this sequence.

Extension of Current Illusion Models

The current version of the detection system includes illusion models for Leans, Graveyard and Coriolis. The models have proven effective at detecting these illusions in actual flight data sets but only under analysis conditions when model values can be modified and flight data examined closely. In several cases, the models helped to direct the focus of the analyst to SD sequences that were similar to the models but represented variations. The most dramatic example is the graveyard spiral sequence that begins with sub-threshold roll and yaw movements (as exhibited in the Strasburg incident) rather than a sequence of rotational washout, illusory rotation, and erroneous counteraction. Future versions of the detection system should include additional versions or extensions to the current illusion models. The leans and graveyard spiral models would also benefit from emerging data regarding the integration of roll and yaw rate information as mentioned above.

Somatogravic Illusion

While the current physiological portions of the SD detection system include a calculation of perceived pitch angle, these values are not used within an illusion model sequence. The somatogravic illusion is a common occurrence resulting from the misperception of pitch angle. Further development of the detection system should include the development of a somatogravic illusion model. Similar to the model of the graveyard spiral sequence, the somatogravic model would start with initiating events that detect pitch perception deltas of specified amounts and lasting for specified time periods. The model might be designed to detect increasing pitch perception deltas as occurs in the inversion illusion. It could also include events for apparent loss of aircraft control, such as high negative vertical velocities when pitched down, or aircraft dynamics indicative of a stall situation when pitched up.

Visual Illusions

The current detection system is focused on vestibular-based illusions. However, there are a host of visual illusions that seriously effect pilots during flight. While it is unknown exactly how such illusions could be modeled, a research and development process focused on this goal could dramatically increase the applicability of an SD detection system, and we have some hunches based upon our experiences. As an example, the HUD tape analysis would have benefited from a visual illusion component.

Evaluation of Pilot Position Assumption

A number of simplifying assumptions were made during the development of the initial vestibular perception calculations. In each case, the purpose of the assumptions was to simplify the modeling process. While the ability of the models to detect SD under analysis conditions has been demonstrated, future versions of the detection system may need to use higher fidelity perception calculations. This may be especially true when the system is integrated with actual cockpit systems. The following is a list of these assumptions as focus areas for future efforts:

- We assumed that the pilot was positioned at the aircraft center of gravity (CG) such that aircraft angular and linear accelerations could be applied directly to the vestibular system. Since the pilot is typically not located at the CG, we need to determine if the resulting changes to vestibular inputs are large enough to affect the accuracy of the detection system. This is especially problematic as the effect may be different for each different type of aircraft.
- We used linear approximations to calculate the angular velocity and acceleration values. We need to determine if representing more accurate aircraft aerodynamics affects the accuracy of the detection system. This is especially problematic as the effect may be different for each different type of aircraft. For example, linear approximations may be acceptable for a small single-engine Cessna, but inadequate for an F-16.

- We assumed that the pilot kept his head position in line with the aircraft. Small movements of the head will cause the actual inputs to the vestibular system to differ from the motions of the aircraft. We need to determine if head motions represent a large enough effect on perception or if they can be considered secondary to the larger inputs from the aircraft motion. In cases where we have head position data, we should use them. If the data set does not have head position data, then we cannot use them and will continue to use simplifying assumptions.

4.2 Improvements to the Aiding System

The combination of pilot workload, aircraft state, and countermeasure presentation developed during this project has proven to be effective in aiding time to recovery from unusual attitudes. Enhancements to this system may further increase its effectiveness. The following are descriptions of some of the ideas for future research and development in this area.

Workload & Stressor Assessments

To further enhance SOAS, we need to calibrate our SAVVOY workload scores to more accurately assess pilot workload in all of the sensory channels in which we are interested. This should include the effects of stressors, such as fatigue, combat for a new pilot, "go pills," etc. There are indications in the research that the effects of these types of stressors on vestibular physiology can alter how spatial disorientations occur. Alion/MA&D has a great deal of experience with accounting for human stressors in military systems, and this expertise could be of great value in determining the effects such stressors would have on pilot workload.

Countermeasure Habituation and Sensory Fatigue

Another necessary enhancement to the application of countermeasures is to more accurately account for habituation and sensory fatigue to determine timing for the various countermeasures. Using human physiology information, we could ensure that cues are less likely to be ignored due to habituation and sensory fatigue. For example, in Phase I, we learned that tactile cues should be used for a maximum of 10-20 seconds due to the likelihood of habituation.

4.3 SOAS Detection and Aiding System Testing and Integration

While SOAS performed well during the testing and experiments performed during this project, there is more that needs to be done to fully integrate the detection and aiding components. The working relationship developed with USAFA during the course of this project could be a key element in continuing these efforts. A large multi-year research plan could be generated if their facilities can be maintained and if a USAFA counterpart is available to oversee the research and cadet involvement. The following are suggestions for additional integration and testing that needs to be done in collaboration with USAFA and others.

SOAS Evaluation

While we were able to capture flight test data to further calibrate and validate our models, we did not conduct a full flight test experiment of SOAS due to resource constraints. Although, our models functioned well within the analysis environment, a set of flight test experiments is necessary to validate SOAS. One of the flight tests, for example, should explore the precise timing relationship between visual, voice, and tactile cues and commands.

Simulator Integration
During the course of this project, we started the process of integrating the countermeasure presentation sequence with a flight simulation system in preparation for an experiment designed to test the efficacy of SOAS. Simulator availability issues prevented us from completing this effort. Future work should involve integrating SOAS with a motion-based simulator, a higher fidelity stationary simulator, and/or a centrifuge-based simulator as part of further development and testing.

Helicopter Data with Head Position
We used real flight data sets from the AF, Navy and NTSB but did not obtain any from the Army. Specifically we would like to evaluate the detection system with SD events that occurred in helicopter flights. Such events are of interest because of the unique rotary dynamics and the potential availability of head position data through the head mounted targeting systems.

Detection System False Positive Evaluation
While we obtained and used real flight data sets from SD incidents, we did not obtain any that represented combat maneuvers without the occurrence of SD (e.g., Red Flag data). Even though SDAT detected SD incidents, it needs to be evaluated for false positives. This will require the use of additional flight data sets and perhaps model modifications.

SD Detection Certainty and Visibility
The most likely false SD detections for a cockpit system will be when the pilot is in a VFR environment. Visual dominance clearly impacts SD. If SDAT/SOAS could determine that the pilot is visual and attending to his/her orientation, that would greatly improve our SD certainty level assessment. At the AsMA conference in May 2006, Art Estrada of the US Army Aeromedical Research Lab at Ft Rucker presented the initial successes of an airborne visibility indicator. Such a system could provide data to SOAS/SDAT in a fully integrated future cockpit.

Transition to an Actual Cockpit System
In addition to all the testing and integration efforts already presented, more is needed in order for SOAS to be ready for an actual integrated cockpit system. Certainly a thorough process of code verification as well as further validation testing is needed. In addition, the process of integrating it within the cockpit software environment will likely require working with a flight systems development company. Finally, there will be the FAA's process of certification as a flight ready system.

4.4 Spatial Disorientation Research

There is much to do to more fully understand both the depth and breadth of the SD problem. The following is a list of potential research efforts that would provide additional information and understanding of SD.

Mission Impact Evaluation
Disorientations that do not result in the loss of the aircraft or crew may still have effects on mission completion. For instance, the time lost while regaining orientation may negatively impact mission time lines. A thorough evaluation of these effects may show that SD is an even greater problem than currently believed. Efforts could include:

- Poll all active military pilots for their personal SD stories and how they survived, plus asking about the mission impact of the SD event.
- Analyze all military and NTSB accident data sets looking for any SD link. SD has been under-appreciated particularly in formal GA accident investigations, and there is much we could do if that link were more fully articulated. The Aviation Safety Reporting System (ASRS) database should be examined for SD incidents, as well.

Foreign Country SD Comparison
In the US, SD tends to be underreported because of a stigma associated with its occurrence. It would be useful to understand how pilots and safety personnel in other countries view the problem. If it is viewed as a more socially neutral medical condition in other places, there may be a way such information could be used to change negative US attitudes and thereby promote safety. Such an educational effort could include dramatic presentations of SD (such as the HUD tape) to begin frank discussions of the problem with safety personnel who will protect pilot confidentiality.

4.5 SDAT Software Enhancements

The current version of the SDAT software functions well. However, new features and additional ideas are always part of the software development process. As part of further tool development we would like to work with personnel from flight safety and accident investigation teams to better understand their practices and needs. Such efforts will likely indicate changes or refinements to the tool that will allow it to better support those needs. The following is a list of other features and functions that could be added in future versions of SDAT:

- Freeze axes in 3DAnimator to view actual and perceived motions in one or two axes alone.
- Explore a 'batch' execution mode that allows the user to select a range of values for the various SD conditions (e.g., roll threshold of 1.1 to 1.5 in increments of 0.1). The issues for such a version include control of combinations and permutations and how the output would be presented.
- Save SDAT outputs in Excel spreadsheets, with an analysis as a single workbook and each execution as a worksheet within the workbook.
- Automatic interpolation for data files with blank cells of data files. The manual interpolation process is laborious.
- Re-develop SDAT to run in Linux. Many users prefer not to use Windows based applications, so a Linux version would expand our compatibility and reach more potential users.

4.6 Applications to Other Topic Areas

The focus of this project has been on modeling and supporting pilots in situations of spatial disorientation. However, there are a number of other areas where either the SD models or the model-based approach could be applied. Human orientation of one kind or another is a problem for subject areas such as space flight, scuba divers and firefighters. It may be possible to use a similar model-based approach to develop systems to support personnel in such environments. The remainder of this section includes three topic areas for future work.

Human Performance Modeling Accident Investigation System

Human Factors professionals have long been part of accident investigation teams but have rarely had the use of automated assessment tools. A group of researches from the NTSB, FAA, NASA, AF, Navy and Army have been looking into the use of human performance models as part of accident investigation. They are interested in the creation of a tool or tools very similar to SDAT that support investigation teams. In addition to the SD models, human performance could be assessed using models of fatigue, workload, speech rate and other stressors to name a few. It is our sense that this expansion from SD analyses into broader human performance issues represents a strong potential for future R&D funding.

Possible Medical Contributions

SDAT has great potential for the medical industry, specifically in the health of elderly patients who are prone to slips and falls. Falls are the leading cause of injury deaths among individuals over age 65, and a contributing factor in 40% of nursing home admissions (Gillespie, 2004; Tinettie et al., 1988). Approximately 35% of people over age 65 fall. This number increases to 50% for individuals over age 80 (American Geriatrics Society et al., 2001; Chang et al., 2004). The direct costs alone of falls among the elderly are expected to exceed $32 billion by 2020 (Enzi, 2003). Furthermore, fear of falling has been shown to limit the physical and social mobility, and independence of elders (American Geriatrics Society et al., 2001; Chang et al., 2004; Gillespie 2004; Whitney et al., 1999).

There is additional work to be done in this area simply because the amount of research studying the causal relationship between aging and falls is so broad, that it is difficult to identify specific data that can be of use. Additionally, older adults are a very diverse group, and their characteristics vary so much that it is difficult to isolate the specific factors that might affect a fall. Individuals may suffer from loss of balance due to the deterioration of multiple sensors. While it's known that the more risk factors an individual has, the more likely they are to fall, there is little understanding of how specific factors impact each other and/or compound the risk for falling (American Geriatrics Society et al., 2000; Tinetti et al., 1988).

Another area to explore is the distinction between age-related sensory degradation and disease as they affect a person's balance. Lord et al., (2001) note that the level of degradation caused by balance disorders tends to level off, whereas that caused by normal aging continues to decline. Determining how, and at what rate of decline, aging will affect a person's balance would benefit research into prevention assessments and tools and methods for rehabilitation and fall prevention.

Unfortunately, balance/stability assessments and fall prevention are typically reactive measures that are addressed after a person has already exhibited some degree of balance dysfunction or has already fallen. Additionally, performance measures are generally poor at discriminating among those with the lowest levels of functioning (Suthers & Seeman, 2004). There is suspicion that some existing tests are not fine grained enough to pick up impairment (Lord et al., 2001).

Much research has been done in studying falls and fall prevention among the elderly. However, this research is varied and so vast that it is difficult to isolate data that may be particularly relevant for specific areas of concern. One key need is for a central repository for this research that allows users to query specific risk factors and circumstances that can affect a fall.

Finally, in addition to a central database to update and store innovative research into the subject, more research needs to occur outside of a lab setting. Most of what is known about the specifics of falls comes only from self reporting. There are clearly discrepancies in the data collection. In one study of people with dizziness, 24% of participants had fallen in the previous 6 months. "Many of the patients failed to identify causes of falling or to state whether the falling was related to dizziness" (Lin et al., 2002).

Given these challenges in the study of elderly falls, we feel that SDAT has some clear relevance and could be used as a useful tool to further examine the mechanics of a fall. As previously stated, one area we would like to explore in future Phases, is quantifying the visual contribution to spatial orientation. Older adults rely more heavily on visual cues to maintain balance than younger adults who rely more on proprioceptive and vestibular cues (Lockhart, Smith, & Woldstad, 2005). Having a better grasp of the interrelationship between the visual and vestibular sensors would allow us to better isolate the most relevant risk factors for falling. Additionally, establishing a central repository of current, relevant research could enable us to determine SDAT's applicability to balance disorders as a whole, not just among the elder population. Finally, SDAT's modeling capabilities would allow us to vary and simulate the many parameters and contributing factors of a fall. This modeling would enable us to better isolate those risk factors which most affect a person's balance, thus improving the quality of proactive preventive measures and assessments performed by clinicians in the earliest stages of sensory degradation.

UAV and General Applications

Given the prevalence and technological growth in Unmanned Aerial Vehicles (UAVs), our model-based approach could be potentially helpful to combat UAV operator disorientation, with focus placed on the visual sources of SD in UAV control.

There is visual dominance, but other cues impact orientation. Quantifying the visual contribution, as well as other inputs to spatial orientation (e.g., proprioceptive) would ultimately yield an SO model for any application – UAVs and others. Then, depending upon the specific application, other model inputs (e.g., the vestibular contribution) could be added as needed. If we can develop a sophisticated SO model – one that contains visual, vestibular and somatosensory inputs, the applications could be endless – medical (enhancing balance), military (effects of non-lethal energy), and, commercial applications (improving virtual games) – to name a few. Clearly there is ample cause for follow-on research and development.

5 Summary & Conclusion

Phase II accomplishments were numerous and significant, and many were captured within submitted journal articles that will be published within the next year. Improvements to the detection subsystem included:

- Improved models from Phase I for Leans and Coriolis, a Graveyard Spiral model, and an explicit detection of significant differences between actual and perceived pitch angle, roll velocity, and yaw/heading velocity as components of "General Illusion" detection; and,
- Experiments and mishap data analyses that verified and validated model improvements.

Improvements to the aiding subsystem were due to:

- Experiments that verified the usefulness of our SD Icon;
- An experiment that proved the efficacy of voice and tactile commands, used in conjunction with the SD Icon, to improve fighter pilot responses to unusual attitudes; and,
- Testing of context-sensitive multisensory countermeasure timing which included suppressing audio cues and commands in the presence of a pilot's high audio workload.

Both the detection and aiding subsystem improvements were embodied within a single integrated tool (SDAT) that proved its usefulness to accident investigators. SDAT is available to federal government customers under standard SBIR contract terms.

Accomplishments above and beyond the statement of work requirements included:

- A US Patent application;
- Four professional journal articles, one in Russian (published Apr-Jul 05), one submitted to ASEM, and two to IJAP;
- Four professional conference presentations (HCI-Aero 04, WinterSim 04, AIAA-ATIO 05, AsMA 06);
- SD mishap data analyses for the Navy and NTSB, as well as 'extra' ones (T-38, F-16 HUD tape) for AFSC;
- Preliminary thoughts about applying our system and methods to such diverse applications as UAVs and gerontology;

The project team (see author list on the cover and the Acknowledgments) is very proud of its accomplishments throughout the effort's three years (Phase I and II), and we recognize that there is still much to do to help real pilots who experience SD – often with fatal consequences. Many of us are pilots who have experienced SD, and so we are eager to keep contributing to progress in preventing the adverse consequences of spatial disorientation. Fatal SD accidents are preventable, even if SD itself is not entirely preventable.

References

Air Force (Nov, 2001). *Flying Safety*. Washington, DC: author.

American Geriatrics Society, British Geriatrics Society, & American Academy of Orthopaedic Surgeons Panel on Falls Prevention (2001). Guideline for the Prevention of Falls in Older Persons. *Journal of the American Geriatrics Society,* 49:664-672.

Alion Science and Technology Corp./MA&D Operation (2006). *SDAT User Guide*. Boulder, CO: Author.

Andre, A.D., & Wickens, C.D. (1992). Compatibility and consistency in display-control systems: Implications for aircraft decision aid design. *Human Factors, 34*(6), 639-653.

Andre, A.D., & Wickens, C.D. (Oct 1995). When users want what's not best for them: A review of performance-preference dissociations. *Ergonomics in Design*, 10-13.

ASA (1995). *Federal aviation regulations & airman's information manual* (ISBN 1-56027-204-X). Renton, WA: Aviation Supplies & Academics.

Bainbridge, L. (1999). Processes underlying human performance. In D.J. Garland, J.A. Wise, & V.D. Hopkin (Eds.), *Handbook of Aviation Human Factors*. Mahwah, NJ: Lawrence3 Erlbaum Associates, 107-171.

Bass, E.J., Ernst-Fortin, S.T., Small, R.L., & Hogans, Jr., J.T. (2004). Architecture and development environment of an intelligent monitoring aid that facilitates incremental knowledge base development. *IEEE Transaction on Systems, Man, and Cybernetics, Part A, 34*(4). Piscataway, NJ: IEEE, pp. 441-449.

Begault, D.R., & Wenszel, E.M. (1992). Techniques and applications for binaural sound manipulation in human-machine interfaces. *International Journal of Aviation Psychology. 2* (1), 23-38.

Begault, D.R., & Pittman, M.T., (1996). Three-dimensional audio versus head down traffic alert and collision avoidance system displays. *International Journal of Aviation Psychology, 6,* 79-93.

Benson, A. J. (1988). Motion sickness & spatial disorientation. In J. Ernsting & P. King (Eds.), *Aviation Medicine*. London: Buttersworth, 318-493.

Beringer, D.B., & Chrisman, S.E. (1991). Peripheral polar graphics display for signal/failure detection. *The International Journal of Aviation Psychology, 1*(2), 133-148.

Berkley, W.E., & Martin, E.L. (2000). *Spatial disorientation in night vision goggle operations.* San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/Primary%20Flight%20Displays/berkley.pdf.

Bonato, F., Bubka, A., (2006). Chromaticity, spatial complexity, and the perception of self-motion. *Perception 2006, 35*, 53-64.

Box, G. (1979). Robustness in the strategy of scientific model building. In R.L. Launer & G.N. Wilkinson (Eds.), *Robustness in Statistics*. St. Louis, MO : Academic Press, 202.

Braithwaite, M.G., (1997). The British Army Air Corps in-flight spatial demonstration sortie. *Aviation, Space, and Environmental Medicine, 68*(4), 342-345.

Braithwaite, M.G., Beal, K.G., Alvarez, E.A., Jones, H.D., & Estrada, A. (1998). The optokinetic cervico reflex during simulated helicopter flight. *Aviation, Space, and Environmental Medicine*, *69*(12), 1166-1173

Braithwaite, M. G., Durnford, S.J., Crowley, J.S., Rosado, N.R., & Albano, J.P. (1998). Spatial Disorientation in U.S. Army Rotary-Wing Operations. *Aviation, Space, and Environmental Medicine, 69*(11), 1031-1037.

Braithwaite, M.G., Durnford, S.F., Groh, S.L., Jones, H.D., Higdon, A.A., Estrada, A., & Alvarez, E.A. (1998). Flight simulator evaluation of a novel flight instrument display to minimize the risks of spatial disorientation. *Aviation, Space, and Environmental Medicine, 69*(8), 733-742.

Braithwaite, M., Ercoline, W.R., & Brown, L. (2004). Spatial disorientation instruction. In F.H. Previc & W.R. Ercoline (Eds.), *Spatial disorientation in aviation.* Reston, VA: AIAA, 323-378.

Braithwaite, M.G, Hudgens J.J., Estrada, A., & Alvarez, E.A. (1998). An evaluation of the British Army spatial disorientation sortie in U.S. Army aviation. *Aviation, Space, and Environmental Medicine, 69*(8), 727-32.

Brickman, B.J., Hettinger, L.J., & Haas, M.W. (2000). Multisensory interface design for complex task domains. *International Journal of Aviation Psychology, 10* (3), 273-290.

Carswell, C.M., & Wickens, C.D. (1987). Information integration and the object display: An interaction of task demands and display superiority. *Ergonomics, 30*(3), 511-527.

Chang, J., Morton, S., Rubenstein, L., Mojica, W., Maglione, M., Suttorp, M., Roth, E., & Shekelle, P., (March 2004) Interventions for the Preventions of Falls in Older Adults: Systematic Review and Meta-Analysis of Randomised Clinical Trials. *, British Medical Journal* 328: 680-686.

Cheung, R. (2000). *Non-visual spatial orientation mechanisms.* San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/MechanismsStudies/cheung.pdf.

Cheung, B. (2004). *Nonvisual illusions in flight.* In: Previc, R.H., Ercoline W.R., (Eds.) Spatial disorientation in aviation. Reston, VA: American Institute of Aeronautics and Astronautics, 243-275.

Collins, W.E. (1965). Subjective response and nystagmus following repeated unilateral caloric stimulation. Ann Otol, 74, 1034-1055.

Costello, R.G. (1976). Continuous compensatory audio manual tracking. In *Proceedings of Twelfth Annual Conference on Manual Control* (NASA TMX-73, 170). Moffett Field, CA: Ames Research Center, 406-421.

Crocoll, W.M., & Coury, B.G. (1990). Status or recommendation: Selecting the type of information for decision aiding. In *Proceedings 34th Annual Meeting of the Human Factors Society*, Santa Monica, CA: HFS, 1524-1538.

Davenport, C. (2000). *Spatial disorientation: The USAF experience, FY1991-FY2000: How much are we willing to pay*? San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/Mishap%20Studies/Davenport.pdf

Davy, E.C., Dudfield, H.J., & Campbell, J.T. (1997). A review of altitude symbology research for helmet-mounted displays. In R. Jensen (Ed.), *Proceedings of the International Symposium on Aviation Psychology.* Columbus, OH: The Ohio State University, 287-293.

DeHart, R.L., & Davis, J.R. (Eds.) (2002). Fundamentals of aerospace medicine (3rd ed., ISBN 0-7817-2898-3). New York: Lippincott Williams & Wilkins.

Endsley, M.R., & Rosiles, S.A. (1995). Auditory localization for spatial orientation. *Journal of Vestibular Research, 5*(6), 473-485.

Engineering Acoustics, Inc. (2003). See: http://www.navysbir.brtrc.com/cap/briefingsadmin/ea.asp.

Enzi, M. (2003) A bill to direct the Secretary of Health and Human Services to intensify programs with respect to research and related activities concerning falls among older adults. 108th Congress First Session (H.R. 3513).

Ercoline, W.R. (1998). In *Minutes of the 22nd meeting of the DoD flight symbology working group.* Moffett Field, CA: NASA Ames Research Center.

Ercoline, W.R., DeVilbiss, C.A., Yauch, D.W., & Brown, D.L. (2000). Post-roll effects on attitude perception: The Gillingham illusion. *Aviation, Space and Environmental Medicine, 71*(5), 489-495.

Ercoline, W.R., Self, B.P., & Matthews, R. (2002). Effects of three helmet-mounted display symbologies on unusual attitude recognition and recovery. *Aviation, Space and Environmental Medicine, 73*(11), 1053-1058.

Erickson, L., van Erp, J., et al. (2006). Vibrotactile and visual threat cuing with high G threat intercept in dynamic flight simulation. *Proceedings 50th Conference of Human Factors and Ergonomics Society*. Santa Monica, CA: HFES.

Forbes, T.W. (1946). Auditory signals for instrument flying. *Journal of the Aeronautical Sciences,* May, 255-258.

Gallimore, J.J. & Liggett, K.K. (2000). *Implications of spatial sensory reflex research on primary flight display design.* San Antonio, TX: Spatial Disorientation Symposium.

Geiselman, E.E. (1999). Development of a non-distributed flight reference symbology for helmet-mounted display use during off-boresight viewing. In *Proceedings of the 4th Annual Situational awareness in the tactical air environment*, Piney Point, MD, 118-127.

Gillespie, L. (2004) Preventing Falls in Elderly People. *British Medical Journal*. 328:653-654.

Gillingham, K.K. (1992). The spatial disorientation problem in the United States Air Force. *Journal of Vestibular Research, 2*, 297-306.

Gillingham, K.K., & Previc, F.H. (1993). *Spatial orientation in flight* (AL-TR-1993-0022). Wright-Patterson AFB, OH: Air Force Armstrong Laboratories.

Gilson, R.D., Ventola, R.W., & Fenton, R.E. (1975). A kinesthetic-tactual display for stall deterrence. In *Eleventh Annual Conference on Manual Control* (NASA TM X-62,464; under FAA contract DOT-FA74WA-3515). Moffett Field, CA: Ames Research Center, 440-451.

Gomez, G. (2002). Spatial Disorientation: Something old & something new. In *Essays & Articles*. Found with Google search at: http://www.isamindia.org/essays/cme_spatial.shtml

Gopher, D., Weil, M., & Barakeit, T. (1994). Transfer of skill from a computer game to flight. *Human Factors, 36*, 387-405.

Guedry, F.E. (1974). Psychophysics of vestibular sensation. In: Kornhuber H, ed. *Handbook of sensory physiology*. Berlin: Springer-Verlag, 3-154.

Guedry F.E., & Ceran S.J. (1958) Derivation of subjective velocity from angular displacement estimates made during prolonged angular acceleration: Adaptation effects. Ft. Knox, KY. US Army Medical Research Laboratory, Report No. 376.

Guedry F.E., Stockwell C.W., Norman J.W., & Owens, G.G. (1971). Use of triangular waveforms of angular velocity in the study of vestibular function. *Acta oto-laryng 71*,439-48.

Hammer, J.M., & Small, R.L. (1995). An intelligent interface in an associate system. In W.B. Rouse (Ed.), *Human/Technology Interaction in Complex Systems* (Vol. 7). Greenwich, CT: JAI Press, 1-4.

Heinle, T.E. (2001). Spatial disorientation research. In *HSIAC Gateway*, 12(3), 1-3.

Ho, C.Y., & Sarter, N.B. (2004). Supporting synchronous distributed communications and coordination through multimodal information exchange. In *Proceedings of the 48th Annual Meeting of the Human Factors and Ergonomics Society.* Santa Monica, CA: HFES.

Holmes, S.R., Bunting, A., Brown, D.L., Hiatt, K.L., Braithwaite, M.G., & Harrigan, M.J. (2003). Survey of spatial disorientation in military pilots and navigators. *Aviation, Space, and Environmental Medicine, 74*(9), 957-965.

ISO (International Standards Organization) (2002). *ISO 14915-3:2002(E), Annex D: Design issues and cognitive background.*

Jenkins, J.C., Thurling, A.J., Havig, P.R., & Geiselman, E.E. (2002). Flight displays II: Head-up and helmet-mounted displays. In F.H. Previc & W.R. Ercoline (Eds.), *Spatial disorientation in aviation.* Reston, VA: AIAA, 451-507.

Johnson, K.R. (2000). *Spatial disorientation in military aviation*. Presented at the Spatial Disorientation Symposium, San Antonio, TX. Found at: www.spatiald.wpafb.af.mil/library_ san.asp.

Kaczmarek,K.A. (2000). Electrotactile adaptation on the abdomen: Preliminary results. *IEEE Transactions on Rehabilitation Engineering, 8*(4), 499-505.

Kovalenko, P.A. (1991). Psychological aspects of pilot spatial orientation. *ICAO Journal, 46*(3), 18-23.

Lin SI, Tsai TT, Lee IH, Wu YN, (2002) Perception of Unsteadiness in Patients with Dizziness: Association with Handicap and Imbalance. *Journal of Biomedical Science* 9:428-435.

Lockhart, T., Smith, J., and Woldstad, J., (2005) Effects of Aging on the Biomechanics of Slips and Falls. *Human Factors*. Vol. 47, No. 4, Winter 2005, p.709.

Lord, S., Sherrington, C., and Menz, H., (2001) *Falls in Older People: Risk Factors and Strategies for Prevention,* Cambridge: Cambridge University Press.

Lyons, T.J., Ercoline, W.R., Freeman, J.E., & Gillingham, K.K. (1993). Epidemiology of United States Air Force spatial disorientation accidents: 1990-1991. In *Aircraft accidents: Trends in aerospace medicine investigation techniques* (AGARD CP 532:31-1 to 31-11). Neuilly Sur Seine, France: Advisory Group for Aerospace Research and Development.

Lyons, T.J., Ercoline, W.R., Freeman, J.E., & Gillingham, K.K. (1994). Classification problems of U.S. Air Force spatial disorientation accidents, 1989-91. *Aviation, Space, and Environmental Medicine, 65*, 147-152.

McGrath, B.J. (2000). *Tactile instrument for aviation* (Naval Aerospace Medical Research Laboratory Monograph 49). Pensacola, FL: NAMRL.

Meehan, J.W. (2001). Advanced display technologies: What have we lost? *HSIAC Gateway 12*(3), 13-14.

Nall (1999). *1999 Nall Report: Accident trends and factors for 1998*. Report found at http://www.aopa.org/asf/publications/99nall.html.

Nielsen, J. (1994). Heuristic evaluation. In Nielsen, J., and Mack, R.L. (Eds.), *Usability Inspection Methods.* NY: John Wiley & Sons.

Nelson, W.T., Hettinger, L.J., Cunningham, J.A., Brickman, B.J., Haas, M.W., & McKinley, R.L. (1988). Effects of localized auditory information on visual target detection performance using a helmet mounted display. *Human Factors, 40*, 452-460.

Newman, R.L., & Haworth, L.A. (2004). Flight displays II: Head-up and helmet-mounted displays. In F.H. Previc & W.R. Ercoline (Eds.), *Spatial disorientation in aviation.* Reston, VA: AIAA, 451-507.

NTSB (2002). *Aircraft Accident Brief* (AAB-02/02; Accident Number CHI01MA011). Washington, D.C.: Author.

NTSB (2003). *Aircraft accident report: In-flight electrical system failure and loss of control, Jet Express Services, Raytheon (Beechcraft) Super King Air 200, N81PF near Strasburg, Colorado January 27, 2001* (NTSB/AAR-03/01, PB2003-910401, Notation 7358A, Adopted January 15, 2003). Washington, DC: Author.

Okada, T., Grunfeld, E., Shallo-Hoffman, J. & Bronstein, A.M. (1999). Vestibular perception of angular velocity in normal subjects and in patients with congenital nystagmus. *Brain, 122*(7), 1293-1303.

Oman, C. (September 1, 2005) personal communication.

Parsons, R.D. (1970). Magnitude estimates of the oculogyral illusion during and following angular acceleration. *Journal of Experimental Psychology*, *84*, 230-238.

Pines, M. (2003). The mystery of smell: The vivid world of odors. In *Seeing, hearing, and smelling the world* (report from the Howard Hughes Medical Institute). Found at http://www.hhmi.org/senses/d110.html.

Previc, F.H. (1998). The neuropsychology of 3-D space. *Psychological Bulletin, 124*, 123-164.

Previc, F.H., & Ercoline, W.R. (1999). The “outside-in” attitude indicator revisited. *International Journal of Aviation Psychology, 9*(4), 377-401.

Previc, F.H., & Ercoline, W.R. (2001). Trends in spatial disorientation research. *Aviation, Space, and Environmental Medicine, 72*(11), 1048-1050.

Previc, F.H., & Ercoline, W.R. (Eds.) (2004). *Spatial disorientation in aviation* (ISBN 1-56347-654-1). Reston, VA: American Institute of Aeronautics and Astronautics, Inc.

Raj, A.K., Kass, S.J., & Perry, J.F. (2000). Vibrotactile displays for improving spatial awareness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting.* Santa Monica, CA: Human Factors Society, 181-184.

Reising, J., Liggett, K.K., & Munns, R.C. (1999). Controls Displays and workplace design In D.J. Garland, J.A. Wise, and V.D. Hopkin (Eds.), *Handbook of Aviation Human Factors,* Mahwah, NJ: Erlbaum.

Rochlis, J.L., & Newman, D.J. (2000). A tactile display for International Space Station (ISS) extravehicular activity (EVA). *Aviation, Space, and Environmental Medicine, 71* 571-578.

Roscoe, S.N. (1968). Airborne displays for flight and navigation. *Human Factors,* 10, 321-332.

Roscoe, S.N. (2002). Ergavionics: Designing the job of flying an airplane. *International Journal of Aviation Psychology*, 12(4), 331-339.

Sarter, N. & Schroeder, B. (2001). Supporting decision making and action selection under time pressure and uncertainty: The case of in-flight icing. *Human Factors,* 43(4), 573-583.

Scott, W.B. (1999). Automatic GCAS: You can't fly any lower. *Aviation Week and Space Technology, 150*(5), 76-80.

Self, B.P., Breun, M., Feldt, B., Perry, C., & Ercoline, W.R. (2002). Longitudinal assessment of pilot performance using a moving horizon (inside-out), a moving aircraft (outside-in), and an arc-segmented attitude reference display. In *Proceedings of the NATO Symposium, Spatial Disorientation in Military Vehicles*. A Coruna, Spain: NATO.

Sipes, W.E., & Lessard, C.S. (1999). Spatial disorientation: A survey of incidence. In R.S. Jensen, B. Cox, J.D. Callister, & R. Lavis (Eds.), *Proceedings of the Tenth International Symposium on Aviation Psychology*. Columbus, OH: The Ohio State University.

Sklar, A., & Sarter, N. (1999). Good vibrations: Tactile feedback in support of attention allocation and human automation coordination. *Human Factors, 41*, 543-552.

Small, R.L., & Bass, E.J. (2000). Certify for success: A methodology for human-centered certification of advanced aviation systems. In J.A. Wise, & V.D. Hopkin (Eds.), *Human Factors in Certification*. Mahwah, NJ: Lawrence Erlbaum Associates (ISBN 0-8058-3113-4), pp. 139-150.

Small, R.L., Fisher, A.M., Keller, J.W., & Wickens, C.D., (2005). A pilot spatial orientation aiding system (AIAA paper 2005-7431). In *Proceedings of the AIAA 5th ATIO and 16th Lighter-Than-Air Sys. Tech and Balloon Systems Conference.* Arlington, VA: AIAA 1-15.

Small, R.L., Fisher, A.M., Keller, J.W., & Wickens, C.D. (2005). A pilot spatial disorientation aiding system. *International Academy of Human's Problems Aviation Cosmonautics Bulletin 2005 1*(17), 26-45 and *2*(18), 28-38.

Small, R.L., Wickens, C.D., Oster, A.M., Keller, J.W., & French, J.W. (2004). *Multisensory integration for pilot spatial orientation* (AFRL contract F33615-03-M-6360; AFRL Technical Report AFRL-HE-WP-TR-2004-0035). Boulder, CO: Micro Analysis & Design.

Solomonow, M., Lyman, J., & Freedy, A. (1977). Electrotactile two-point discrimination as a function of frequency, body site, laterality, and stimulation codes. *Annals of Biomedical Engineering, 5,* 47-60.

Solomonow, M., Raplee, L., & Lyman, J. (1978). Electrotactile two-point discrimination as a function of frequency, pulse width and pulse time delay. *Annals of Biomedical Engineering, 6* 117-125.

Spence, C. (2002). Multisensory attention and tactile information –processing. *Behavioral Brain Research, 135,* pp. 57-64.

Stapleford, R.L. (1968). Multimodality pilot model for visual and motion cues. *Proceedings of Fourth Annual NASA-University Conference on Manual Control* (NASA SP-192). Ann Arbor, MI: University of Michigan, 47-56.

Stevens, S.S. (1960). The psychophysics of sensory function. *American Scientist,48*, 226-253.

Sundstrom, J.N. (2004). Flight conditions leading to Class A spatial disorientation mishaps in U.S. Air Force fighter operations: FY93-02[Master's Thesis]. Washington, D.C.: The Department of Preventive Medicine and Biometrics of the Uniformed Services, University of the Health Sciences.

Suthers, K., and Seeman, T., (December 12, 2003) *The Measurement of Physical Functioning in Older Adult Populations,* Performance Measurement Workshop Consensus Document. National Institute on Aging, Intramural Research.

Taylor, R.M. (2002). *Capability, cognition and autonomy*. Keynote address to the NATO RTO Human Factors and Medicine Panel Symposium, HFM-084/SY-009. Warsaw, Poland (7-9 October).

Taylor, R.M., Abdi, S., Dru-Drury, R., & Bonner, M.C. (2000). Cognitive cockpit systems: Information requirements analysis for pilot control of automation. In D. Harris (Ed.) Engineering Psychology and Cognitive Ergonomics, Vol. 5, Aerospace and Transportation Systems. Ashgate, Aldershot, pp. 81-88.

Taylor, R.M., Brown, L., & Dickson, B. (2002). *From safety net to augmented cognition: Using flexible autonomy levels for on-line cognitive assistance and automation*. Paper #27, NATO RTO Human Factors and Medicine Panel, Symposium on Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures. La Coruna, Spain (15-17 April).

Taylor, R.M., Shadrake, R., Haugh, J., & Bunting, A. (1995). *Situational awareness, trust and cognitive compatibility: Using cognitive mapping techniques to investigate the relationships between important cognitive system variables*. Presented at the 79th AGARD AMP Symposium on Situational Awareness, Etat-Major de la Force Arienne, Brussells, Belgium (24-28 April).

Tinetti, M., Speechley, M., and Gintner, S. (1988) Risk Factors Among Elderly Persons Living in the Community. *New England Journal of Medicine*, 319(26): 1701-1707.

United States Navy (1991). *United States Naval Flight Surgeon's Manual* (3rd ed.). Pertinent section obtained from: www.vnh.org/FSManual/03/03SpatialDisorientation.html.

United States Army (2000). *Aeromedical Training for Flight Personnel* (FM #3-04.301), Chapter 9. Washington, D.C.: Department of the Army.

Van Erp, J., Groen, E., Bos, J., & Van Veen, H. (2006). A tactile cockpit instrument supports the control of self-motion during spatial disorientation. *Human Factors, 48* (2) 219-228.

van Erp, J.B.F., Veltman, H.J.A., & van Veen, H.A.H.C. (2003). A tactile cockpit instrument to support altitude control. In *Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society.* Santa Monica, CA: HFES, 114-118.

Veronneau, S.J.H. (2000). *Civilian spatial disorientation mishap experience.* San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.Wpafb.af.mil/Mishap%20 Studies/Veronneau.pdf.

Vinje, E.W., & Pitkin, E.T. (1972). Human operator dynamics for aural compensatory tracking. *IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-2*(4), 504-512.

Von Bekesy, G. (1955). Subjective cupulometry. *American Medical Association, Archives of Otolaryngology, 61,* 16-28.

Weinstein, L., & Wickens, C.D. (1992). Use of nontraditional flight displays for the reduction of central visual overload in the cockpit. *International Journal of Aviation Psychology, 2*(2), 121-142.

Whitney, S., Hudak, M., and Marchetti, G., (1999), The Activities-Specific Balance Confidence Scale and the Dizziness Handicap Inventory: A Comparison. *Journal of Vestibular Research*, 9:253-259.

Wickens, C.D. (1984). Processing resources in attention. In R. Parasuraman & D.R. Davies (Eds.) *Varieties of attention*. New York: Academic Press, 63-258.

Wickens, C.D. (1986). The effects of control dynamics on performance. In K.R. Boff, L.Kaufman, & J.P. Thomas. (Eds.), *Handbook of Perception and Human Performance (Volume II),* pages 39.1-39.60. New York: John Wiley & Sons.

Wickens, C.D. (1986). Manual control. In: Boff, K., Kaufman, L., Thomas, J. (Eds.) *Handbook of perception and human performance.* New York: Wiley Interscience, vol. 2, Chapter 40.

Wickens, C.D. (1995). Designing for stress. In J. Driskell & E. Salas (Eds.), *Stress and Human Performance,* Mahwah, NJ: Erlbaum.

Wickens, C.D. (2002). Situation awareness and workload in aviation. *Current Directions in Psychological Science, 11*(4), 128-133.

Wickens, C.D. (2003). Aviation displays. In P.Tsang, & M. Vidulich (Eds.), *Principles and practices of aviation psychology.* Mahwah, NJ: Lawrence Erlbaum, 147-199.

Wickens, C.D., & Carswell, C.M. (1995). The proximity compatibility principle: Its psychological foundation and relevance to display design. *Human Factors*, 37(3), 472-494.

Wickens, C.D., & Hollands, J.G. (2000). *Engineering Psychology and Human Performance.* Upper Saddle River, NJ: Prentice Hall.

Wickens, C.D., Sandry, D., & Vidulich, M.I. (1983). Compatibility and resource competition between modalities of input, central processing, and output: Testing a model of complex task performance. *Human Factors,* 25, 227-228.

Wickens, C.D., Ververs, P., & Fadden, S. (2004). Head-up display design. In D. Harris (Ed.), *Human factors for civil flight deck design.* Burlington, VT: Ashgate, 103-140.

Wickens, C.D., Vincow, M., & Yeh, M. (2005). Design applications of visual spatial thinking. In A. Miyaki, & P. Shah (Eds.), *Handbook of Visual Spatial Thinking*. Oxford University Press.

Wiegmann D, Faaborg T, Boquet A, Detwiler C, et al., (2005) *Human error and general aviation accidents: A comprehensive fine-grained analysis using HFACS* (Report No. AM-05/24). Washington DC: Federal Aviation Administration.

Appendix A. Publications Appendix

Our first publication was our Phase I final report. An excerpt of that was published in a Russian journal as: Small, R.L., Fisher, A.M., Keller, J.W., & Wickens, C.D. (2005). A pilot spatial disorientation aiding system. In V. Ponomarenko (Ed.), *International Academy of Human's Problems in Aviation and Cosmonautics Bulletin, 1*(17), pp. 26-45 & *2*(18), pp. 28-38.

Next was the IJAP paper describing our SD Icon low-fidelity experiment at USAFA. That paper was cleared for public release by the USAFA Public Affairs office, and was accepted by IJAP with some revisions. Publication should be imminent. It appears starting on the next page and is followed by:

- A conference paper for HCI-Aero in Toulouse, France;
- After HCI-Aero, we presented a paper at AIAA-ATIO. Both of the preceding papers were based upon information cleared for public release from the Phase I final report;
- An ASEM article that describes our GAT somatogyral experiment (on 9/28/2006 accepted for publication);
- Another IJAP article draft for the recently completed SOAS test; and,
- An abstract for an ISAP 2007 paper.

Two other conference presentations, which did not require papers – they were slide presentations only – were WinterSim 2004 and AsMA 2006. They are not reproduced here, but have been delivered to our customer and were cleared for public release. In the interest of completeness, we should also mention that we attended AsMA 2004 (where we learned about Creare's modeling SBIR), and staffed an exhibit at AsMA 2005 (where we met many of the key AFSC people with whom we have worked on data analyses since then).

Title: Unusual Attitude Recoveries with a Spatial Disorientation Icon
Running Title: UARs with SD Icon

Authors & Affiliations (at time when research conducted): Christopher D. Wickens (University of Illinois), Brian P. Self (US Air Force Academy professor), Terence S. Andre (US Air Force Academy professor), Tommy J. Reynolds (US Air Force Academy cadet), & Ronald L. Small (Micro Analysis & Design, Inc.)

ABSTRACT

Twenty-two participants (12 with prior flying experience and 12 without), performed a series of trials in a low fidelity flight simulator in which they attempted to recover from a series of unusual attitudes. Two display variables were examined: (1) the attitude display was either a traditional head-up display (HUD) with an inside-out motion and pitch ladder, or an Arc-Segmented Attitude Reference (ASAR) display; and (2) a command icon that pointed to the appropriate airplane rotation for recovery direction in pitch and roll was either present or absent. The results revealed that the icon speeded the initial correction and reduced the number of roll

reversal errors, while the traditional HUD decreased the total time to recovery. Experienced pilots were more disrupted by the ASAR display than were novices.

INTRODUCTION

Human factors researchers have investigated different forms of aircraft display symbologies since Sperry and Doolittle performed the first instrument-only flight in 1929. These two pioneers of aviation recognized that the attitude indicator (AI) was of paramount importance in maintaining controlled flight in low visibility environments, and continued to improve upon their design. Today the AI is recognized as perhaps the only way to prevent spatial disorientation (SD), which costs the Department of Defense over $300 million per year in accident investigations, family compensation, and aircraft reconstruction. "On average, the USAF [United States Air Force] alone loses five aircraft with aircrews (and sometimes with passengers) each year due to spatial disorientation, and most of these are related to loss of attitude awareness" (Ercoline et al., 2000, p. 489). To help prevent these mishaps, it is necessary to provide the pilot with the most intuitive and effective AI possible (Self et al., 2002).

Two different types of approaches can be taken to assist in attitude recovery. One approach, based on the **status display design**, presents information regarding the current attitude status. However, as a status display the commonly used inside-out moving horizon attitude indicator has sometimes been criticized for inducing control reversals, as pilots confuse the moving element on the display (the horizon) with the element in motion in the real world (the airplane) (Roscoe, 2002; Previc & Ercoline, 2001; Kovalenko, 1991). When this design is incorporated on a head-up display or HUD (often the most critical source of attitude information for the Air Force pilot), dangers of motion and attitude confusion can be amplified because the skeletal nature of the HUD symbology prevents color coding of ground and sky (typical of the head-down AI). Several approaches have been implemented on HUDs to allow better discrimination of extreme pitch down from pitch up attitudes (Newman & Haworth, 2004). These include for example, dashed (negative pitch) versus solid (positive pitch) markers for each rung of the pitch ladder, or bent pitch ladder bars, whose angle indicates the degree of pitch.

As an alternative to the traditional Air Force HUD with its inside-out pitch ladder (Fig. 1a), some designers have proposed the Arc-Segmented Attitude Reference (ASAR) display (North, 2003; Jenkins et al., 2002; Geiselman, 1999). This display (Fig. 1b) has the advantage that a level attitude (zero pitch and roll) is indicated by a simple and easily perceptible semi-circle object (a horizontally oriented half of a "grapefruit," which has led to this being called the "grapefruit display"). Deviations from level pitch are rendered by the amount of arc displayed. Deviations in bank are rendered by whether the center of the arc is rolled left or right. Thus when the grapefruit disappears entirely, it corresponds to a direct sky pointing attitude (90° nose up; just as the world would disappear entirely in the pilot's forward view). When the grapefruit forms a complete circle, it corresponds to a direct ground pointing attitude (90° nose down; just as the full circle of the earth would be rendered looking directly at it from space). In any state in between, an arc is formed whose direction corresponds to bank (Newman & Haworth, 2004). The roll information acts similarly to the traditional HUD symbology: as the actual aircraft rolls counterclockwise, the arc appears to rotate clockwise. In the example shown in Figure 1b, the aircraft is pitched up (because the arc length is short) and rolled right.

While the ASAR display is appealing in its concept, few objective evaluations have been accomplished which compare and contrast it with more traditional HUDs for attitude recovery. Those that have been performed have had inconsistent outcomes, some favoring the ASAR (Geiselman, 1999; Jenkins et al., 2002; Ercoline et al., 2002), and some not (Davy, Dudfield and Campbell, 1997). Reasons for this inconsistency remain varied. One problem is that the relative novelty of the ASAR may conflict with the greater familiarity of the traditional HUD for experienced pilots. Another is that, when presented as a HUD, the ASAR presents attitude in a very different frame of reference from that of the visual world beyond; whereas in the inside-out (IO) version, the two reference frames are identical and aligned (i.e., “conformal”). This alignment would not of course be characteristic were the display represented in an off-boresight helmet mounted display (HMD), and explains why the greater benefits to the ASAR appear to emerge when it is evaluated as a candidate for off-boresight viewing in an HMD (Jenkins et al., 2002; Ercoline et al., 2002).

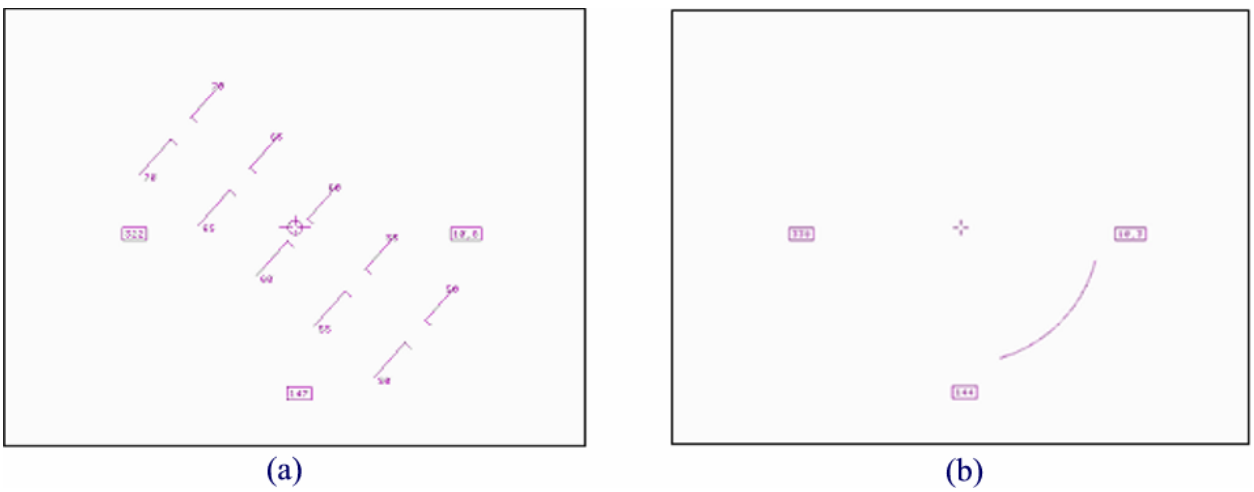

Figure 1. (a) F-16 IO display and (b) ASAR display. Both displays show the airplane rolled right 45° and pitched up 60°.

The second, complementary (and not mutually exclusive) approach to unusual attitude recovery is that of a **command** display that provides direct instructions to the pilot on how to point the aircraft to recover a level attitude from an unusual attitude. Such commands might use a synthetic voice, and have also been investigated by implementing various visual pointing devices. For example some HUDs have included an “Auggie arrow” (named after its inventor, Bill Augustine; that points in the roll direction to the horizon (Newman & Haworth, 2004). Also, an “articulated pitch ladder” will bend in such a way that the two limbs on both sides of the boresight will point toward the horizon (Newman & Hawarth, 2004), such that raising or lowering pitch in response to the visual command will restore a level attitude. Rather than embedding such command information in the pitch ladder itself, Bainbridge (1999) has suggested a command icon using a simple geometric shape that is easily interpreted. We chose a diamond to represent pitch and roll (Fig. 2). This icon can be distorted in shape such that the more acute corner points in the direction (vertical and or horizontal) for which a correction is required to restore a level attitude. Figure 3 shows our SD icon superimposed on an F-16 IO and on an ASAR display. To our knowledge, this particular format of command display has not been evaluated as a means of attitude recovery.

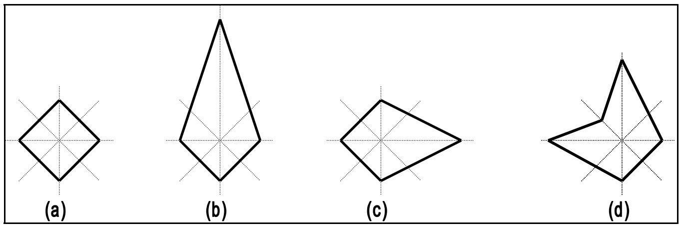

Figure 2. SD icon snapshots for an aircraft whose state is: (a) 0° Pitch, 0° Roll; (b) -90° (down) Pitch, 0°Roll; (c) 0° Pitch, -45° (left) Roll; and, (d) -45° Pitch, +45°Roll. The icon in the figure points in the direction(s) to correct for these states.

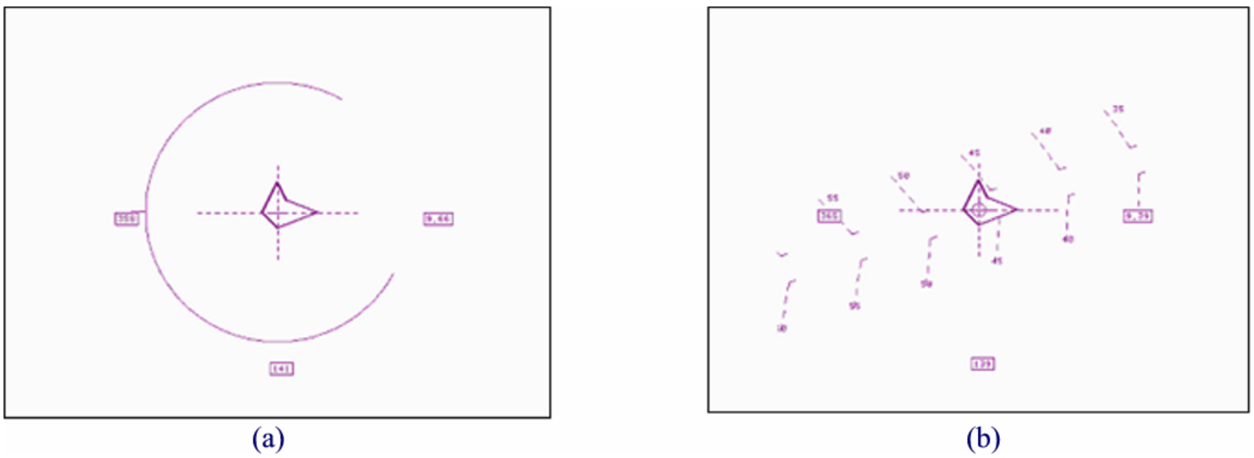

Figure 3. (a) F-16 IO display with icon and (b) ASAR display with icon. Both displays show the airplane rolled left 75^{o} and pitched down 45^{o}.

Although separate vertical and horizontal arrows could be used, instead of the icon, two facets of the icon suggest that it should be a superior representation. First, as a single geometric object, it is more likely to capture attention than the smaller arrows. Second, the two dimensions are integrated in one object, and hence, research suggests that users are more able to perceive the **joint implications** of both, should a correction in both axes be required (Beringer and Chrisman, 1991; Carswell and Wickens, 1987; Wickens and Carswell, 1995).

In the current experiment, we examine the efficacy of both HUD design (F-16 IO and ASAR) and the pointer icon in restoring a level attitude from an unusual one, in a low fidelity simulation, using both experienced and novice pilots.

METHODS

Participants

The study utilized two groups of participants, a novice and an experienced group. The novice group was comprised of 15 Behavioral Science students from the US Air Force Academy. The ages of the novice participants ranged from 17-23 and included 4 females and 11 males. Eight of the novice participants had some training in AIs or aircraft operations. The experienced group was comprised of seven cadets who were soaring instructor pilots, cadet aviation instructors, or who held a private pilot license with more than 100 hours of flight experience.

The mean age of participants in the expert group was 22.5 years, and all participants in this group were male.

Materials

The test apparatus consisted of a 17-inch computer monitor which presented the image from the Dell OptiPlex GX200 with Intel Pentium 3 processor. The joystick was a CH Products F-16 flight stick. The program is known as the Flight Performance Assessment Simulation System (F-PASS), programmed by NTI, Inc. of Dayton, OH. The F-PASS simulates an American F-16 fighter aircraft; flight data are recorded at 20 Hz.

Procedure and Design

As participants entered the lab, they were first presented with their informed consent documents and the participant's bill of rights. Once given a chance to examine the documents and subsequently sign them, the participants were given a pretest survey designed to gather demographic information and to gauge their level of experience with using attitude indicators. Next, the purpose of the study was briefed. Practice trials were administered once the participants felt comfortable with the way each display responded and reacted to stick inputs. During the "free-flight" exposure to the experimental conditions, the practice trials consisted of two simulated daytime trials in which computer-generated terrain was visible beyond the attitude display on the screen, and eight trials in which only the display symbology was visible on a black background. These conditions represented visual meteorological conditions in the day, and instrument meteorological conditions at night, respectively. All attitudes were reflected in the practice trials. Immediately after the participants finished the practice trials, they were exposed to one of the four display formats (combination of icon presence and IO/F-16 or ASAR HUD format), and received eight unusual attitude recovery trials. In each trial, the participant was looking at a blank display, when the attitude indicator appeared representing the aircraft in an unusual attitude. Each unusual attitude consisted of one of two possible values of pitch (+ or – 45°) and four possible values of roll (90°, 75°, 60° and 45°). The latter were randomly presented to the left or right, and the order of pitch and roll attitude combinations was quasi-randomly presented. Participants were instructed to provide roll input to level the wings, and then correct their pitch attitude. Following the presentation of the eight recovery trials with a given display format, instructions were presented for the next type of format for the participant, and this process was repeated until all four formats were experienced. Each participant received all four formats in a counterbalanced order.

Three dependent measures were recorded on each trial: (1) the time to initial stick input, (2) number of roll reversal errors (RREs), and (3) time to full recovery to straight and level flight (where "straight and level" was defined as the simultaneous occurrence of less than 5 degrees of both pitch and roll). Each participant's measures were calculated for each trial, but then averaged across the eight unusual attitudes to generate three single measures for each participant. Participants were also asked to subjectively rate on a 5-point scale each display format according to ease of use, intuitiveness, and if it effectively helped them perform the task. They were then asked to rank order the four display formats by preference and to rate if the addition of the icon helped them to effectively accomplish their task.

RESULTS

A multivariate analysis of variance (MANOVA) first examined the overall significance of the full 2 (experience) x 2 (display) x 2 (icon) design for all dependent measures. Results from the MANOVA indicated a significant difference for display format, $F(3,18) = 21.09$, $p < 0.001$ and icon presence, $F(3,18) = 10.78$, $p < 0.001$. Although the average data of the experienced group showed better performance across all dependent measures, the MANOVA did not indicate a significant difference between the two groups, $F(3,18) = 1.427$, $p > 0.10$. However, there was a marginally significant effect for the experience x display interaction, $F(3,18) = 2.71$, $p = 0.075$, indicating experts and novices were affected differentially by the ASAR and IO displays. Because the MANOVA test did not indicate any significant ($p < 0.05$) differences between experts and novices in the effects of the two dependent variables, the data for both groups were combined and analyzed using univariate ANOVA tests for the 2 (display) x 2 (icon) design. The full data set for all participants (expert and novice) is provided in Table A1-1.

Table 1. Descriptive statistics for all participants (n=22).

		Measure					
Display	**Icon**	**Input**		**RRE**		**Recovery**	
		M	SD	M	SD	M	SD
ASAR	SD Icon	0.9941	0.29	0.7273	1.39	12.6127	2.72
	No SD Icon	1.2873	0.78	2.3182	1.94	12.9418	3.19
IO	SD Icon	1.0323	0.39	0.3636	0.79	10.5345	3.10
	No SD Icon	1.3314	0.71	1.5909	1.44	11.1373	3.09

Initial Stick Input

The initial stick input was 0.3 seconds faster with the icon than without, $F(1,21) = 10.03$, $p < 0.01$ but was not influenced by display format, nor did the two independent variables interact.

Roll Reversal Errors

As illustrated in Figure 4, the number of roll reversal errors was also substantially reduced by the icon's presence, $F(1,21) = 33.58$, $p < 0.001$ to a value of one-third of that when the icon was absent. Display format provided a marginally significant benefit by reducing the number of roll reversal errors, $F(1,21) = 4.23$, $p = 0.05$. The mean number of roll reversal errors was slightly lower with the IO display than with the ASAR display. There was no interaction of display format with icon presence.

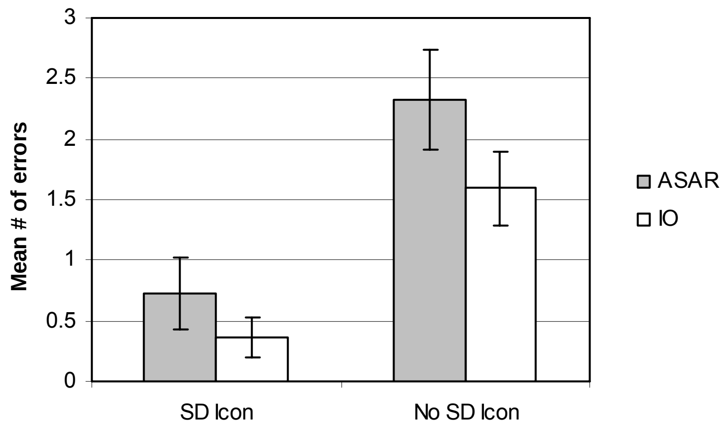

Figure 4. Number of roll reversal errors as a function of display format and icon presence.

Time to Full Recovery

Finally, the total time to full recovery, while not influenced by the presence of the icon, was significantly influenced by display format, being approximately 1.9 sec faster with the IO HUD, than with the ASAR HUD, $F(1,21) = 35.47$, $p < 0.001$. Again, there was no interaction between the two independent variables.

Experience x Display Interaction

As indicated in the MANOVA test, there was a differential effect of display format for experts vs. novices. Conducting a univariate ANOVA on the experience x display format interaction showed a significant result for the time to full recovery measure, $F(1,20) = 6.52$, $p < 0.05$. Expert recovery time was more severely slowed by the ASAR display (3.03 seconds slower than the IO display) when compared to novices (1.45 seconds slower than the IO display). This difference is shown in Figure 5.

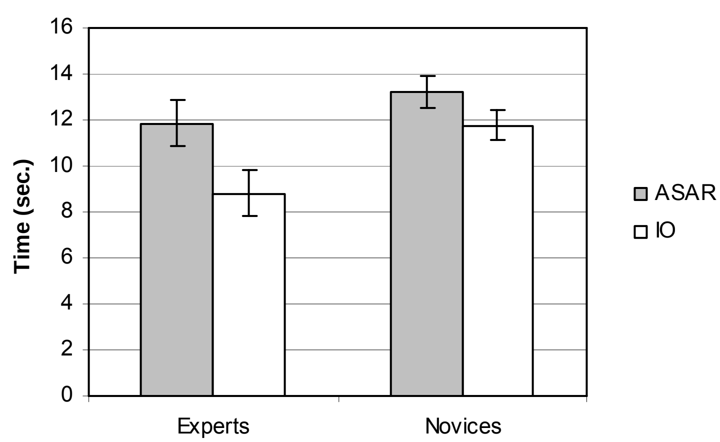

Figure 5. Time to full recovery as a function of display format and experience.

Subjective Ratings

The subjective ratings for ease, intuitiveness, and effectiveness at completing the task all followed the same trends, as shown in Figure 6. The traditional (F-16 IO) HUD with the icon consistently rated the highest, followed closely by the ASAR with icon. The ASAR alone was by far the least preferred display format. Only three out of the 22 subjects did not feel that the addition of the icon helped them perform their task effectively; the overall rating was a 4.16 out of 5.

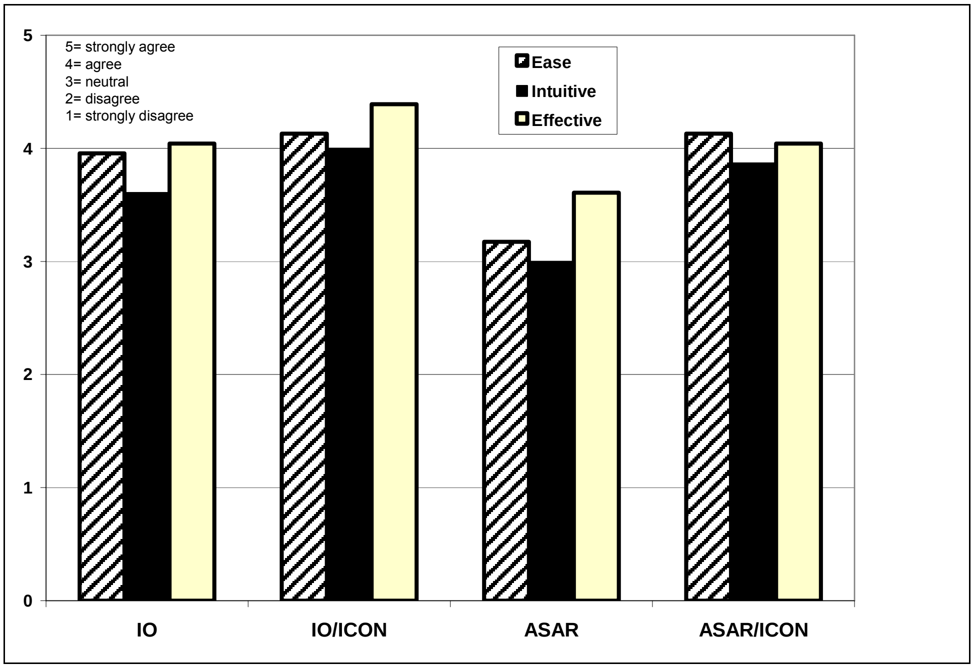

Figure 6. Subjective ratings of the four combinations of display format and icon.

DISCUSSION

The results of the current study are fairly straightforward, with nearly identical effects observed for both novices and higher time pilots (although neither group had flown with HUDs). For both groups, the icon was beneficial in speeding the initiation of the original correction, and in assuring that corrections were in the appropriate direction in the roll axis. Such an advantage of presenting the unambiguous command icon implicitly signals some of the problems with pure status attitude information (the non-icon conditions) that have been associated with the ambiguity of the artificial horizon (Previc & Ercoline, 1999; Roscoe, 2002; Wickens, 2003), violating as it does the principle of the moving part (Roscoe, 1968). This would certainly be the case for the F-16 HUD display, in which an "inside out" motion of the display symbology is used. This motion stereotype is also violated with the ASAR display, since the moving element on the display does not correspond to the airplane. Other features of this display, discussed below, also may have hampered attitude recovery, and hence led to the observed benefit of the icon.

Both the performance and the subjective data clearly indicate the advantage of the icon display as a **command** display. By now, a growing body of research has documented the advantages of command displays (over status displays) as decision aids in high time-stress environments (Crocoll & Coury, 1990; Sarter & Schroeder, 2001; Wickens, 2003). These displays eliminate the cognitive step of inferring the necessary action from the observed status, by directly presenting that action. Clearly, recovery from an unusual attitude is a prototype of such a time-stress situation.

Somewhat more puzzling was the clear emergence of a cost for the ASAR display, relative to the F-16 (IO) HUD symbology, as measured in total recovery time and in roll reversal errors. While neither pilot group was familiar with HUD symbology per se, we can possibly relate the ASAR cost to the phenomenon of negative transfer of motion stereotypes. Members of both groups, and particularly the expert group, had some experience flying with the standard IO moving horizon attitude display. The F-16 HUD symbology we used preserves this motion, whereas the ASAR symbology is less consistent, presenting a motion pattern that does not conform to the view forward from within the cockpit. Furthermore, we might expect that symbology to hinder more those with greater experience on the inside-out motion pattern, and indeed this expectation was confirmed, as the experts showed a full three-second recovery time cost, whereas the novice cost was less than half of that.

How then does this clear finding of an ASAR cost converge with the various examples of ASAR benefits discussed above (Geiselman, 1999; Jenkins et al., 2002; Ercoline et al., 2002)? The answer, presumably, is that those benefits had been observed primarily when the ASAR was used as a component of a head-mounted display with off-boresight viewing. In these instances, the relation between display movement and airplane movement is decoupled in any case, so motion conformity of rotation between the airplane and the displayed airplane symbols become less critical; and indeed it may be better to have the more cognitively compatible moving airplane display (Wickens et al., 2005). It is when the display and airplane axes are aligned, as in the current study, that the benefits of the same reference frame (moving airplane) are more likely to emerge.

IMPLICATIONS AND APPLICATIONS

The two implications of this experiment are fairly straightforward. First, a command icon can be an extremely useful tool for attitude recovery, so long as it is presented in a manner that is clearly distinguishable from any status information (Wickens, 2003). Second, the ASAR display, with its relatively unconventional attitude representation may be effective for off-axis viewing in a helmet-mounted display, but probably is not advisable for standard forward-looking HUD symbology. This issue of how to resolve these two possibly conflicting guidelines is important, but beyond the scope of the current paper, and is addressed in detail by Wickens et al. (2004).

Naturally the current results need to be accepted with some caution as to their generalizability, given the lack of flight experience in combat aircraft of all participants, and given the low fidelity of the simulation used. Another important issue concerning generalizability relates to the paradigm used here, with an "instantaneous" loss of spatial orientation rather than, as in normal flight conditions, circumstances in which it may take several seconds to evolve from an "oriented" to a "disoriented" attitude. We justify our paradigm choice here on two grounds. First, much spatial disorientation is categorized as "type 1" when the orientation loss is unconscious (that is, the pilot is unaware of the loss); therefore when the pilot abruptly does transition to "type 2" (becomes aware), this transition is typically an abrupt one, triggered by a sudden glance at the instruments. Second, it is also the case that the loss of spatial orientation happens when the pilot is engaged in head-down concurrent tasks, and so again, realization that orientation is loss, occurs with a discrete glance at the instruments – essentially replicating the procedure of the current experiment.

As part of an Air Force program to reduce SD-caused mishaps, the command icon represents a significantly helpful step and should be further tested as a next step in actual flight with Air Force rated pilots. Furthermore, it is important to note that the SD icon is just one small part of an overall effort to reduce the adverse consequences of SD. The overall effort should include: pilot selection; pilot training; pre-mission briefings to review the risks of SD; flight data collection; and, post-flight analyses to determine the actual conditions under which pilots are more susceptible to SD. Post-flight analyses will also suggest which SD countermeasures are most effective during actual missions as research results transition into operational use. Further details regarding a more comprehensive approach to reducing SD-caused mishaps are in Small et al. (2005).

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REFERENCES

Bainbridge, L. (1999). Processes underlying human performance. In D.J. Garland, J.A. Wise, & V.D. Hopkin (Eds.), *Handbook of Aviation Human Factors.* Mahwah, NJ: Lawrence Erlbaum Associates, 107-171.

Beringer, D.B. and Chrisman, S.E. (1991). Peripheral polar graphics display for signal/failure detection. *The International Journal of Aviation Psychology, 1*(2), 133-148.

Carswell, C.M., & Wickens, C.D. (1987). Information integration and the object display: An interaction of task demands and display superiority. *Ergonomics, 30*(3), 511-527.

Crocoll, W.M., & Coury, B.G. (1990). Status or recommendation: Selecting the type of information for decision aiding. In *Proceedings 34th Annual Meeting of the Human Factors Society.* Santa Monica, CA: HFS, 1524-1538.

Davy, E.C., Dudfield, H.J., & Campbell, J.T. (1997). A review of attitude symbology research for helmet-mounted displays. In R. Jensen (Ed.), *Proceedings of the International Symposium on Aviation Psychology.* Columbus, OH: The Ohio State University, 287-293.

Ercoline, W.R., DeVilbiss, C.A., Yauch, D.W., & Brown, D.L. (2000). Post-roll effects on attitude perception: The Gillingham illusion. *Aviation, Space, and Environmental Medicine, 71*(5), 489-495.

Ercoline, W.R., Self, B.P., & Matthews, R. (2002). Effects of three helmet-mounted display symbologies on unusual attitude recognition and recovery. *Aviation, Space, and Environmental Medicine,* 73(11), 1053-1058.

Geiselman, E.E. (1999). Development of a non-distributed flight reference symbology for helmet-mounted display use during off-boresight viewing. In *Proceedings of the 4th Annual Situational awareness in the tactical air environment*, Piney Point, MD, 118-127.

Jenkins, J.C., Thurling, A.J., Havig, P.R., & Geiselman, E.E. (2002). Flight test evaluation of the nondistributed flight reference off-boresight helmet-mounted display symbology. In C.E. Rash, & C.E. Reese (Eds.), *Proceedings of the SPIE Helmet- and Head-Mounted Displays VII*, 341-355.

Newman, R.L., & Haworth, L.A. (2004). Flight displays II: Head-up and helmet-mounted displays. In F.H. Previc & W.R. Ercoline (Eds.), *Spatial disorientation in aviation.* Reston, VA: AIAA, 451-507.

Kovalenko, P.A. (1991). Psychological aspects of pilot spatial orientation. *ICAO Journal, 46*(3), 18-23.

Previc, F.H., & Ercoline, W.R. (1999). The “outside-in” attitude indicator revisited. *International Journal of Aviation Psychology, 9*(4), 377-401.

Previc, F.H., & Ercoline, W.R. (2001). Trends in spatial disorientation research. *Aviation, Space, and Environmental Medicine, 72*(11), 1048-1050.

Roscoe, S.N. (1968). Airborne displays for flight and navigation. *Human Factors, 10*, 321-332.

Roscoe, S.N. (2002). Ergavionics: Designing the job of flying an airplane. *International Journal of Aviation Psychology, 12*(4), 331-339.

Sarter, N. & Schroeder, B. (2001). Supporting decision making and action selection under time pressure and uncertainty: The case of in-flight icing. *Human Factors, 43*(4), 573-583.

Self, B.P., Breun, M., Feldt, B., Perry, C., & Ercoline, W.R. (2002). Longitudinal assessment of pilot performance using a moving horizon (inside-out), a moving aircraft (outside-in), and an arc-segmented attitude reference display. In *Proceedings of the NATO Symposium, Spatial Disorientation in Military Vehicles.* A Coruna, Spain: NATO.

Small, R.L., Fisher, A.M., Keller, J.W., & Wickens, C.D. (2005). A pilot spatial orientation aiding system (AIAA paper 2005-7431). In *Proceedings of the AIAA 5th ATIO and 16th Lighter-Than-Air Sys Tech. and Balloon Systems Conference*. Arlington, VA: AIAA, 1-15.

Wickens, C.D. (2003). Aviation displays. In P. Tsang & M. Vidulich (Eds.), *Principles and Practices of Aviation Psychology* (Chapter 5, 147-200). Mahwah NJ: Erlbaum.

Wickens, C.D., & Carswell, C.M. (1995). The proximity compatibility principle: Its psychological foundation and relevance to display design. *Human Factors, 37*(3), 473-494.

Wickens, C.D., Vincow, M., & Yeh, M. (2005). Design applications of visual spatial thinking. In A. Miyaki , & P. Shah (Eds.), *Handbook of Visual Spatial Thinking.* Oxford University Press.

Wickens, C.D., Ververs, P., & Fadden, S. (2004). Head-up display design. In D. Harris (Ed.), *Human factors for civil flight deck design.* Burlington, VT: Ashgate, 103-140.

Multisensory Integration for Pilot Spatial Orientation

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Spatial disorientation (SD) is a normal human response to accelerations in flight. Its cost to the US military is over $300 million per year, with comparable costs to US civil aviation. Despite significantly increased research over the past decade, the rate of accidents caused by SD has not decreased. While the most recent research emphases have been on understanding the physiology of SD, the translation of the new knowledge into tools (e.g., training, displays, automation) that help pilots avoid SD and minimize its effects if it does occur, has not occurred. Our research goals were to apply multisensory countermeasures (CMs) to SD based on human sensory models and the pilot's workload. We assert that multisensory CMs, applied in an intelligent fashion, are needed and possible.

Spatial disorientation, multisensory displays, intelligent aiding

INTRODUCTION

Spatial disorientation, simply referred to as vertigo until becoming the subject of scientific research, is a normal response to physiologically confusing stimuli in flight. Humans evolved to perceive motions on land relative to the earth's surface. In flight, human senses can give the brain erroneous orientation information. Everyone who flies will eventually experience some SD illusions; some pilots will experience them more acutely than others.

The seriousness of SD phenomena to the flight environment cannot be overstated. Of 323 of the most serious mishaps in the US Air Force from 1991-2000, 20.2% were SD related [1]. Further, it is estimated that 89% of general aviation SD events are fatal [2]. Holmes et al. [3] have estimated that roughly 80% of pilots have experienced SD incidents, although these usually do not lead to mishaps. SD mishaps are often fatal, accounting for the loss of about 40 lives per year in the US military [4, 5], with a cost of over $300 million per year; US civil aviation has comparable SD costs. Increasing research has not decreased the rate of accidents caused by SD [6].

The conflict between one's senses and reality typically lead to SD illusions, and has received much recent research attention. Understanding the physiological causes of SD is important to solving the problem. For example, how much do optical illusions contribute to SD-related accidents? How effective is a particular attitude display in helping to maintain spatial orientation (SO)? Some answers are beginning to emerge. For example, Gomez [7] asserts, "90% of all inputs to the brain that give the sense of orientation are visually acquired." This assertion implies that SO displays should be visual, as opposed to auditory or tactile displays, which, presumably, contribute only 10% of the orientation inputs to the brain. However, the SD problem is too important to rely on only one sensory channel. Also, because SD is often due to a sensory conflict or distraction, using only one sense (vision) to combat it is ill advised. A multisensory approach is needed.

For our purposes, we define SD as a loss of attitude awareness, which is a subset of one widely accepted definition of SD [see 8]. Often this loss of attitude awareness is caused by degraded visual information regarding the true horizon, plus the input of misleading vestibular (inner ear) signals. Therefore, we focus on models of vestibular-based illusions, the Leans and Coriolis illusions. For brevity, we only describe our Leans model. For details about Coriolis and other illusions, as well as general information about SD and SO, see [9].

The most common SD illusion is the Leans [3, 8], which usually entails an erroneous feeling of roll. A typical case is as follows [10]: In the clouds, the pilot unknowingly enters a turn at a vestibular sub-threshold rate of less than about 2°/second so that the semicircular canals do not sense the turn. If the pilot then becomes aware of the aircraft's roll angle (e.g., by looking at the aircraft's attitude reference information) and abruptly returns to level flight, he or she will now receive a vestibular sensation of an opposite roll. If the pilot continues to rely upon flight instruments to maintain a level attitude, he or she may also *lean* toward the erroneously perceived upright (hence the illusion's name). If the pilot does not rely upon the instruments at this point, but rather the (incorrect) vestibular signal of upright, he or she will return the aircraft to its original roll angle. Without awareness and conscious correction, the roll may lead to a pitch down attitude and a loss of altitude, which may progress to the point of ground impact. This progression is illustrated in Figure 1, which is the model of the Leans that we use.

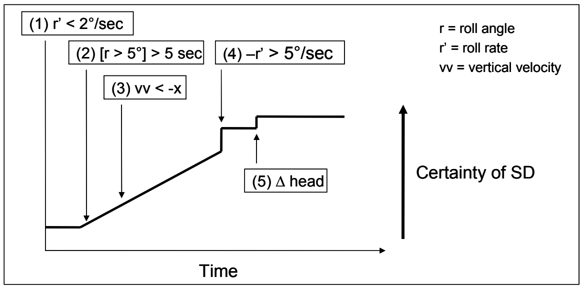

Figure 1. Leans model.

COUNTERMEASURES

How does/should the aviation community deal with this problem? There is a range of measures to prevent and counter SD. Techniques include: pilot selection and training; pre-mission risk analyses and awareness; real-time cockpit systems, such as visual displays, audio attitude cues, automated audio recovery commands, haptic or tactile displays, and ground collision avoidance systems; and, post-accident analyses. Much research has been done to enhance visual displays to help prevent or counter SD. Again, reference [9] thoroughly describes such issues. Our contribution to display enhancement builds upon work by Bainbridge [11], who recommends simple geometric shapes to ease interpretation. We offer the SD icon shown in Figure 2, which would appear on one or more visual displays under the control of an intelligent cockpit aiding system [12].

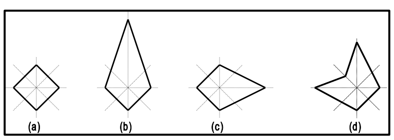

Figure 2. SD icon: (a) 0° pitch & roll; (b) +90° pitch, 0° roll; (c) 0° pitch, 45° right roll; and, (d) +45° pitch, 45° left roll.

A MULTISENSORY SD AIDING SYSTEM

Our approach is to intelligently apply multisensory CMs to aid the pilot in avoiding SD's bad consequences. To do this, we model the pilot's SD illusion severity, the pilot's workload, and the severity of the resulting flight situation. As an SD event worsens and as the aircraft enters unusual attitudes that could result in an accident, our multisensory CMs become more intrusive. For example, if we assess that the pilot has a mild case of the Leans, but is close to the ground and visually task-loaded, our intelligent SD Aiding System triggers intrusive audio and tactile CMs. As the pilot recovers, CMs become less intrusive. If the situation worsens (e.g., imminent ground impact), CMs become more urgent, which might include auto-recovery. Figure 3 shows the architecture of our system; Figure 4 depicts the remediation network used to determine the intrusiveness of CMs.

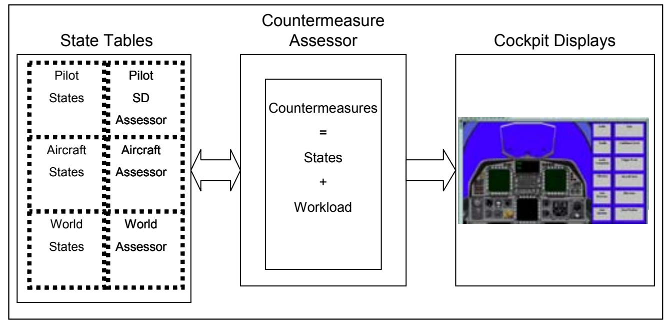

Figure 3. Spatial disorientation aiding system architecture.

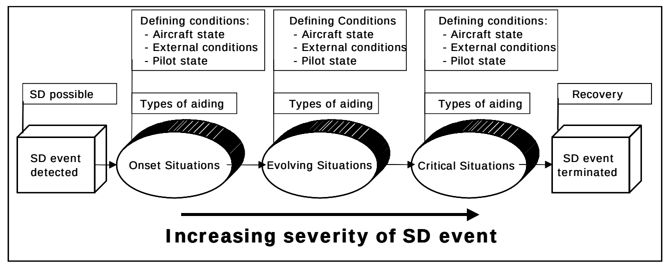

Figure 4. SD remediation network.

CONCLUSION

Our real-time prototype illustrates how our SD Aiding System responds to three scenarios: a simulated Leans illusion, a simulated Coriolis illusion, and actual flight data from an F-16 mishap attributed to SD by the Air Force Safety Center. Our initial research proved the feasibility of using an intelligent SD aiding system to trigger multisensory CMs to help combat SD. Ongoing research will validate our models and test the efficacy of our approach via pilot-in-the-loop experiments.

ACKNOWLEDGMENTS

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REFERENCES

1. Davenport, C. (2000). *Spatial disorientation: The USAF experience, FY1991-FY2000: How much are we willing to pay*? San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/Mishap%20Studies/Davenport.pdf.
2. Nall (1999). *1999 Nall Report: Accident trends and factors for 1998*. Report found at http://www.aopa.org/asf/publications/ 99nall.html.
3. Holmes, S.R., Bunting, A., Brown, D.L., Hiatt, K.L., Braithwaite, M.G., & Harrigan, M.J. (2003). Survey of spatial disorientation in military pilots and navigators. *Aviation, Space, and Environmental Medicine, 74*(9), 957-965.
4. Braithwaite, M. G., Durnford, S.J., Crowley, J.S., Rosado, N.R., & Albano, J.P. (1998). Spatial

Disorientation in U.S. Army Rotary-Wing Operations. *Aviation, Space, and Environmental Medicine, 69*(11), 1031-1037.

5. McGrath, B.J. (2000). *Tactile instrument for aviation* (Naval Aerospace Medical Research Laboratory Monograph 49). Pensacola, FL: NAMRL.
6. Ercoline, W.R., DeVilbiss, C.A., & Lyons, T.J. (1994). Trends in USAF spatial disorientation accidents – 1958-1992. In *Proceedings of the SPIE Conference* (A95-12001-01-54 in Orlando, FL). Bellingham, WA: Society of Photo-Optical Instrumentation Engineers, 257-260.
7. Gomez, G. (2002). Spatial Disorientation: Something old & something new. In *Essays & Articles*. Found at: http:// www.isamindia.org/essays/cme_spatial.shtml.
8. Benson, A. J. (1988). Motion sickness & spatial disorientation. In J. Ernsting & P. King (Eds.), *Aviation Medicine*. London: Buttersworth, 318-493.
9. Previc, F.H., & Ercoline, W.R. (Eds.) (2004). *Spatial disorientation in aviation*. Reston, VA: American Institute of Aeronautics and Astronautics.
10. Gillingham, K.K., & Previc, F.H. (1993). *Spatial orientation in flight* (AL-TR-1993-0022). Wright-Patterson AFB, OH: Air Force Armstrong Laboratories.
11. Bainbridge, L. (1999). Processes underlying human performance. In D.J. Garland, J.A. Wise, & V.D. Hopkin (Eds.), *Handbook of Aviation Human Factors.* Mahwah, NJ: Lawrence Erlbaum Associates, 107-171.
12. Hammer, J.M., & Small, R.L. (1995). An intelligent interface in an associate system. In W.B. Rouse (Ed.), *Human/Technology Interaction in Complex Systems* (Vol. 7). Greenwich, CT: JAI Press, 1-4.

A Pilot Spatial Orientation Aiding System
(AIAA-ATIO conference paper)

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Spatial disorientation (SD) is a normal human response to accelerations in flight. Its cost to the US military is over $300 million per year, with comparable costs to US civil aviation. Due to significantly increased research over the past decade, some progress is being made in helping pilots avoid SD's adverse consequences (i.e., mishaps, incidents, or accidents). We used a multi-sensory model-based approach to intelligently trigger SD countermeasures. Results for two simulated and one actual SD event were very promising, and indicate that the next research step should include verifying and validating our models, and evaluating our spatial orientation aiding system (SOAS) via pilot-in-the-loop simulations and flight tests. SOAS evaluates the aircraft motions, pilot workload, aircraft state, and world state to determine if the pilot is probably suffering from SD, and, if so, SOAS applies a range of countermeasures to assist the pilot in recognizing the SD and recovering. Countermeasures include visual cues, audio cues, audio recovery commands, tactile cues, and olfactory cues, as well as the more extreme measures of auto-recovery and auto-ejection (to save the pilots life, only if all other countermeasures have failed).

Introduction

Spatial disorientation (SD) is a normal human response to accelerations in flight. Its cost to the United States (US) military is over $300 million per year[1,2] with comparable costs to US civil aviation.[3] Despite significantly increased research over the past decade,[4,5] the SD-related accident rate has not decreased, although Braithwaite[6] reports some promising trends for Army helicopter operations based upon realistic SD training sorties. *Everyone* who flies will eventually experience some SD phenomena; some pilots will experience them more acutely than others.

The conflict between one's senses and reality, which is at the core of the SD problem, has received much recent research attention.[7,8] Understanding the physiological causes of SD is essential to solving the problem, but is outside the scope of this paper; excellent references exist.[5,8,9] The inability of pilots to accurately and intuitively perceive aircraft position without reliance upon visual cues (from flight instruments or the outside world) is a major crux of the aviation mishap problem. Maintaining spatial orientation cannot be done in present-day flight operations unless one is attending to the appropriate visual cues. Unfortunately, many of an aviator's distracting secondary flight tasks are also of a visual nature, so continuous attention to one's spatial orientation cannot be maintained using current visual displays. Furthermore, attention is also diverted to non-visual sources; for example, the distraction of voice

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communications or problem solving.[10] Holmes and colleagues[11] identify "distraction/task saturation" as an important factor in their list of causes of spatial disorientation. The problem concerning the allocation of limited attentional resources is compounded by the fact that attentional resources will be drawn to more natural and salient body (vestibular) cues concerning orientation, which in the environment of flight are not veridical. In other words, the problem of SD in flight is not caused merely by attentional limitations; rather, the problem is the formation of an incorrect, yet persuasive, subconscious tendency to rely upon vestibular orientation cues.

A tendency to not recognize hazards during moments of distraction has been noted by SD researchers. The typical SD mishap occurs when visual attention is distracted from the aircraft's orientation instruments and the horizon is not visible or not being monitored.[12] For example, all US Air Force SD mishaps during 1990-91 were categorized as unrecognized SD (Type 1).[13] In other years, relatively few SD mishaps were attributed to SD that was recognized (Type 2) or SD that was completely incapacitating (Type 3). In the past, the aerospace community came to realize that "pilot error" was not a sufficiently specific description for the cause of an airplane crash. Now we must avoid the temptation to consider our job complete when we have identified some general human psychological state as the cause of an accident. As Lyons and colleagues[14] have said concerning SD mishaps: "…if both an attention deficit and SD are part of the chain of events leading to an accident, each should be separately identified as a causal factor if elimination of either would have prevented the accident." This advice makes very good sense in the short term. In the long term, what is needed is to incorporate separately tabulated factors into a model that can accurately predict the amount of variance accounted for by each factor contributing to human error in flight. This requires a commitment to differentiate factors that are usually aggregated *a priori*.

Clearly, SD is a huge problem for US military and civilian aviation, with likely parallels around the world. Consequently, it is a problem worthy of a depth and breadth of research. Solutions do not have to solve the entire problem; even a partial solution can contribute to saving lives and aircraft. Because SD is often due to a sensory conflict or distraction, using only visual displays to combat it is ill advised. A multisensory approach is needed. Another key to combating SD is to prevent its adverse consequences. As an SD event deteriorates, the sequence of multisensory countermeasures should increase in intrusiveness. To properly trigger such countermeasure sequences, we use SD illusion models, pilot workload models, and situational consequence models in our Spatial Orientation Aiding System (SOAS). The following sections briefly explain the illusions we selected to model, current and suggested countermeasures, our multisensory SOAS, and our preliminary results.

Illusions

Spatial disorientation accidents have been referred to as those in which the pilot crashes because the seriousness of the situation does not become evident until it is too late. There are numerous, well-documented illusions that are generated by visual-vestibular conflicts. This section describes two illusions that we studied in depth and then modeled.

The most common SD illusion in flight is the Leans,[11,15] which entails an erroneous feeling of roll. A typical case occurs in the following scenario:[16] In poor visibility conditions, the pilot has very slowly entered a turn, probably unknowingly, at a sub-threshold rate of less than 2°/sec (i.e., below Mulder's constant) so that the pilot's vestibular system provides no sense of rotation. If the pilot then becomes consciously aware of the aircraft's bank angle (e.g., by looking at the instruments), and intentionally returns the bank to the true level attitude, he or she will now receive a vestibular sensation of an opposite bank. If the pilot continues to rely upon flight instruments to maintain a level attitude, he or she may also *lean* in the orientation of the incorrectly perceived upright (hence the illusion's name). If the pilot does not rely upon the instruments at this point, but rather the intuitive (vestibular) signal of upright, he or she will return the aircraft to its original bank angle. Without awareness and conscious correction, the bank will lead to a gradual pitch down attitude, a loss of altitude, and an increase in airspeed. A potential side-to-side see-sawing process of correction and re-entry may continue until the pilot is so disoriented that recovery to straight-and-level flight is difficult, if not impossible. In this case, the *Leans* may progress into a more severe loss of altitude, which ends with ground impact.

The *Airman's Information Manual* describes the Coriolis illusion as the "most overwhelming of all illusions in flight." It occurs during "a prolonged constant-rate turn that has ceased stimulating the…[vestibular] system," (i.e., washout) when there is an abrupt head movement that creates "the illusion of rotation or movement in an entirely different axis" (page 645).[17] The resulting tumbling sensation can be incapacitating. The Coriolis illusion often results in the pilot's loss of aircraft control, which can have catastrophic results if there is no other pilot to assume control. The power of the Coriolis illusion to deceive is further supported by the finding in a recent survey that it was the most prevalent of those found in 141 pilots attending a course at Randolph Air Force Base, Texas in 1997-98.[18] We selected the Coriolis illusion as the other prototypical illusion for our research because it is among the most common flight illusions (#5 in the list compiled in Ref. 11) and is often fatal. It causes overwhelming disorientation and so is an appropriate illusion to combat.

In summary, the physiological circumstances underlying many spatial disorientation illusions are as follows: Aircraft motion, sometimes coupled with head motion, provides illusory vestibular signals to the brain. Normally, when salient visual cues are available, visual dominance will allow the vestibular cues to signal the correct orientation and motion. However, when the visual cues are degraded or missing, the compelling vestibular signals may dominate, and illusions may occur. Knowledge of how these illusions begin and progress provides suggestions for countermeasures, which we address in the following section. We chose the Leans and Coriolis illusions because of their prevalence and because they represent a slow-onset and a quick-onset SD event, respectively. Our assumption was that if we could address both illusions, we would expect that we could help remedy other visual-vestibular illusions.

Countermeasures: A Layered Approach

This section describes a multisensory approach to preventing, minimizing, or compensating for pilot spatial disorientation. Since human spatial orientation has such a large visual component, we describe visual displays in some depth. Audio and tactile displays follow, and then an intelligent system approach to applying the various SD countermeasures. All of these technologies fit within a layered approach to combating SD.

We suggest a layered approach to improving pilot attitude awareness and reducing the negative consequences of SD events. Improving current cockpit displays (i.e., head-down, head-up, and helmet-mounted) and incorporating new technologies (e.g., audio, tactile) requires a methodology for integrating and testing all of the salient technologies and techniques to determine which ones are the best at enhancing attitude awareness, preventing SD events, and minimizing the impact of any SD events that do occur. A layered approach begins with pilot training and mission pre-briefings, and extends through improved display technologies and recovery aiding, into post-flight data analyses to better understand, categorize, and track SD events to determine the actual operational effectiveness of the various techniques advocated to improve SD accident statistics.

Recent research has explored new approaches to addressing SD: better attitude information for head-down, head-up, and helmet-mounted displays; audio displays; and, tactile displays. Which of these approaches, or combination of approaches, is best at reducing SD? Because the potential of each individual technology to reduce SD has not been established (theoretically or empirically), it is difficult to postulate the "best" combination. Rather, it seems that whichever displays are best in a given set of circumstances at helping pilots to recognize and recover from that SD event, then those are the displays that should be used. How do researchers know which displays are best for different SD scenarios? There is nothing in the current literature to suggest an answer; therefore, it will be difficult to devise the "best" combination. In fact, a "best" combination or solution may not be possible for the foreseeable future, due to individual pilot variability, mission susceptibility, risk factors, and circumstances. But, we can theoretically and empirically determine **good** combinations of countermeasures to help combat SD.

Determining the best approach for converting unrecognized into recognized SD events should take a human cognition and workload modeling approach. When visual senses are overloaded or deemed unreliable, the audio channel may be useful. A tactile (vest) attitude display may also help, but research into tactile displays is in its infancy. A presently untested sense for SD is the sense of smell. Smells are very compelling[19] and may be useful during incapacitating SD events to help pilots "snap out of it." Such an olfactory system will need sensors to know that the pilot is incapacitated, and the smell used must be penetrating, harmless, and easily carried aboard aircraft.

When the pilot does not recognize an SD event, intelligent aiding systems may help. For example, audio recovery instructions have shown some early utility with SD events in simulators, according to experiments done at the Air Force Research Laboratory (AFRL). They key is for the aiding system to recognize when SD is causing an unusual attitude or dangerous situation. The emphasis of such systems ought to be on preventing the bad *consequences* of SD events, since it will be virtually impossible to prevent all SD events due to the normal physiological response to most events that induce SD.

Therefore, the best approach is a layered one that seeks to enhance attitude awareness and combat SD via multiple techniques: training improvements, operational awareness, better displays (visual, auditory, tactile, olfactory), intelligent automation, and rigorous post-flight SD event analyses to better understand and characterize SD events, which should also indicate the operational effectiveness of the various SD-combating techniques. We briefly address each layer in the following subsections.

Training can help pilots recognize the types of circumstances that yield SD so that they will be vigilant for the same or similar circumstances.[16] Training also needs to be enhanced and should include classroom discussion, simulator and centrifuge training, and aircraft demonstrations. While there is some risk in actual flight demonstrations, the risk of not doing so is reflected in the rates of SD accidents in military and civil aviation over many decades. Clearly, not all SD event categories can be demonstrated, but a significant cross-section could be.[6] The teaching of SD situation recognition is a major contribution to prevention. And, pilots who are more vigilant for SD-inducing circumstances are better equipped to avoid or to successfully combat them. It is also important to teach recovery techniques for the riskiest situations to reduce the number of incapacitating SD events. The most prevalent factor in USAF SD incidents is attention management,[2] a skill that can (and should) be improved with training.[20]

Pre-briefings could reduce some SD event severity. Certainly, pre-briefings could increase the odds of any SD event being recognized rather than unrecognized. Since the environmental conditions that increase susceptibility to SD are known, mission pre-briefings will be timely reminders to pilots, thus reducing the likelihood of an SD event being unrecognized. The Indian Air Force has developed a checklist enumerating SD threats, and has even anticipated the increased threat of SD from supermaneuvers in such aircraft as the F-22, F-35, V-22, and the Apache helicopter.[21]

US Air Force statistics about contributing factors to SD incidents point to conditions in which the pilot is highly susceptible to SD. All of this knowledge and experience should be highlighted during mission planning and pre-briefings so that pilots can be vigilant. Weather conditions, moonless night flights over the desert, and night vision goggle (NVG) use, are all known to be risk factors.[22] Reminding pilots of the relevant mission risk factors and what to do if SD occurs, refreshes their earlier training, and is another important layer in a comprehensive approach to mitigating the effects of SD.

Because the primary source of information to the pilot is visual, because the visual modality is the most compatible modality for presenting spatial information relevant to attitude,[23] and because SD incidents are most prevalent in poor weather or at night (when the view of the true horizon is obscured or gone), it is not surprising that a key countermeasure in combating SD is in the design of **effective** visual displays. Sadly, many advances in this direction are lacking, because design has generally focused on providing the necessary information to support spatial orientation, but not on the ideal **format** in which that information should be depicted most naturally or intuitively. One of the major culprits appears to be the focus on using the round dial display, even as cockpit displays have evolved to include computer generated imagery, where the electromechanical constraints associated with the round dial are no longer relevant. Attitude displays (head-down, head-up, and helmet-mounted) have symbology to help recognize unusual or undesirable attitudes that usually result from SD (cf., Figure 1). Such symbology should be enhanced based upon the latest research results.[24,25] In addition, how to accommodate the visual limitations caused by NVGs is ripe for further research.[22]

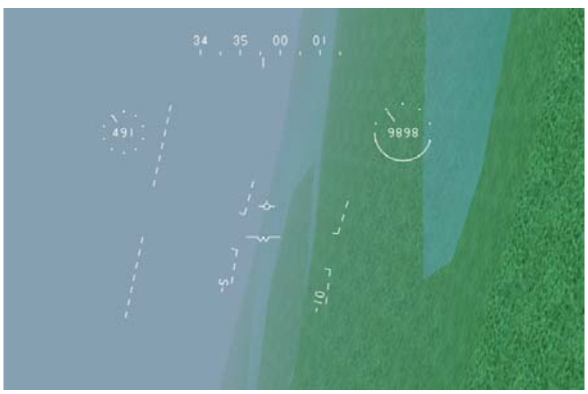

Figure 1. US military standard head-up display (HUD) symbology.

Recent results[26,27] suggest the development and testing of a display icon that uniquely conveys the existence of an SD-induced unusual attitude and what to do about it. We propose that this icon conform to characteristics that make it easy to detect, interpret, and act upon, without confusion or control reversal errors (CREs). Such a display icon should be a unique simple geometric shape that portrays the relevant

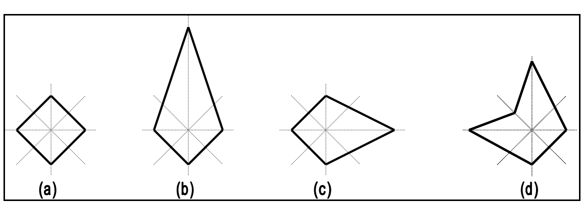

Figure 2. SD icon snapshots (pitch/bank): (a) 0°/0°; (b) +90°(up)/0°; (c) 0°/+45°(right); and, (d) +45°/-45.

information in an easily understood format.[26] Using the principles espoused by Bainbridge,[26] an SD Icon should portray pitch and bank in a way that makes it clear what the attitude is, and what pilots must do to recover from unusual attitudes. Figure 2 illustrates our concept for an icon to be presented on visual displays.

Advances in panoramic displays, symbology, and new display types do not answer the question of how to best use each cockpit display to enhance pilot attitude awareness and to combat SD. Ercoline,[28] a leading SD researcher, has challenged the need for helmet-mounted display (HMD) attitude symbology, and has suggested a study using four experimental objectives: agree on symbology across the US military services; agree on flight tasks; develop a protocol; and, establish research facilities and staff. The point is that there is not an expert consensus about whether or how to use HMD symbology to prevent SD events from becoming mishaps.

Pilots maintain attitude awareness via their visual scan; but, when SD occurs, the typical feeling is of a conflict between their vision and somatic senses. It feels like their vision is lying to them. Therefore, relying primarily on visual display cues to recover attitude awareness is probably less effective than using a combination of multisensory displays. Recent research has explored using auditory and tactile senses to combat SD. This recent research is laudable precisely because SD accident rates have remained constant during the decades when attitude information appeared only on visual displays. Clearly, a new emphasis is needed. We next examine auditory, then tactile countermeasures for SD.

A key feature of visual displays is their ability to capitalize upon parallel processing, or separate resources, so that, for example, ambient vision could process a peripheral horizon, even as focal vision was involved with other aspects of visual perception.[29,30] A long history of research on multiple processing resources,[10] has revealed that the auditory modality can process information in parallel with the visual, and therefore the auditory *channel* should be able to support spatial orientation in an otherwise visually loaded, or visually impaired (e.g., by nystagmus) environment. In making this suggestion however, it should be noted that the auditory modality is inherently less compatible for providing spatial information, than is the visual.[23]

Potentially useful auditory information can be classified into four categories; the first two are discrete or symbolic, and the second two are continuous or analog:

1. **Discrete alerts**. This describes the standard advantage of the omni-directional and intrusive auditory modality for presenting critical warnings. For example, a unique tone or single word can warn pilots that they may be experiencing SD.
2. **Verbal commands**. Verbal commands can provide effective corrections about what to do to recover from an SD incident, as the verbal modality is well suited for command displays,[31] and there are well-documented successes in aviation for audio commands, such as the “climb climb” resolution advisory in the Traffic Collision Avoidance System, or the “pull up” command of the Ground Proximity Warning System.[32] In both cases, the commands directly signal an action, and the verbal modality can successfully “break into” a visually saturated processing stream. It is easy to envision how a simple verbal command of the correction required to pull out of an unwanted attitude could be effective, (e.g., “bank left”), assuming that such a command was offered following the correct inference of aircraft state.
3. **Continuous localization**. A fairly extensive body of research has established the ability of auditory tones or sounds to convey information as to the location of their source, by mimicking the central and peripheral acoustic effects of the two ears.[33,34] Such systems typically employ intensity and phase differences between the two dichotically presented

sounds, to accurately signal the azimuth of a perceived sound, relative to the momentary orientation of the head. A very naturalistic or *ecological* signal of head orientation relative to the source of sound can be provided, offering good support in airborne target acquisition studies.[33-35] However, an unfortunate aspect of such systems is that they are far less accurate in conveying elevation information than azimuth information. Since SD is often due to a misperception of which direction is up rather than which direction is forward, auditory localization may be ineffective as an SD countermeasure.

4. **Continuous orientation**. To provide a continuous signal of which way is up typically requires some non-naturalistic assignment of head orientation to tone pitch and or intensity. In this regard, effective demonstrations of auditory compensatory tracking have been provided by various researchers.[36-39] Typical is the assignment made by Vinje and Pitkin[37] in which the ear in which a tone was presented represented the side of an error (in this case, an attitude displacement from level), while the pitch of the tone represented the magnitude of the error. Such a system would create an increasing pitch tone, as the aircraft rolls to one side or the other. It has been found fairly effective in supporting continuous compensatory tracking, although greater benefits are often realized when the auditory cues are redundant with visual cues.

An important feature in designing such auditory systems for SD applications is that the pilot can gain greater information from the time-varying trend of tones and sounds, than from the absolute pitch or intensity levels of such sounds. For example, an **increasing** pitch (or volume) can signal that things are getting worse. But there is no particular **level** of pitch (or volume) that can be used to intuitively convey a particular state (e.g., middle C, or 70 decibels corresponds to 45° of bank). A second issue is whether the direction of a tone (e.g., left or right ear) should correspond to the status of error, or the necessary command to correct the error. Will a rising tone in the right ear intuitively signal that the right wing is rising (and therefore the plane is banking to the left), or the converse? Such a mapping of tone to state must be done consistently and intuitively by the pilot, otherwise control reversals will result (as has been observed for the visual moving horizon display being confusing). The importance of this intuitive mapping is heightened for the SD application, because the usage of any auditory cuing will be required when the pilot may already be in a stressed state, in which non-intuitive mappings are likely to be ignored or misinterpreted.[40]

In summary, audio tones are good as alerts of undesirable states, and audio commands are effective in directing recoveries from unusual attitudes; but tones are not intuitive for orientation cueing.

Early research into tactile displays was by Gilson and colleagues[41] who described a lever system attached to the control yoke. Their goal was to indicate angle of attack (AOA) to pilots via a lever that would push into the pilot's hands to indicate which direction the pilot should move the yoke (push or pull) for the optimal AOA during low speed flight phases (i.e., takeoff, approach, and landing). Solomonow and colleagues[42,43] examined human sensitivity to vibrotactile displays, the early forerunners of today's tactile vests. Their goal was to determine appropriate vibration frequency ranges, pulse widths, and body locations for maximum sensitivity and information transfer. Kaczmarek examined adaptation and stimulus threshold changes with repeated vibrotactile stimuli.[44]

Recent developments include full tactile vests, used to transfer altitude deviation and attitude information.[12,45-50] Tactile systems are typically used to complement visual or audio displays, not in isolation, because of their lack of comparable sensitivity. Research into this promising display technology is ongoing due to its relative ease of implementation, and due to positive early results.

In many respects the creation of tactile displays can match applications 1, 3, and 4 of auditory displays discussed above, and there is, indeed, a fairly close correspondence between the two modalities. Tactile stimulation can (1) alert,[51] it can (3) convey azimuth location information (for example, a stimulus presented from a belt around the waist), and it can (4) convey a sense of orientation (e.g., differential elevation between the left and right sides). Research on tactile channels for orientation however is considerably sparser than for auditory channels.[45,49] Both auditory and tactile modalities would probably suffer from habituation, and so must be used sparingly and in concert with other sensory inputs.

Visual displays can convey precise spatial information. However both auditory and tactile displays offer the potential to combat SD (or maintain spatial orientation) because of their capability to provide information in parallel with an overloaded visual system.[10] Indeed auditory localization displays have provided useful spatial information in orienting toward targets in three-dimensional (3D) space,[33,34] as well as in continuous tracking.[36,37,39] More recently, tactile and haptic displays have been explored for similar purposes.[46,49] While it is clear that information from these displays **can** be processed in parallel with visual information, thereby potentially exploiting multiple resources, it remains to be seen the extent to which such parallel processing **will** take place in the high stress and workload of spatial disorientation.

New technologies, such as 3D audio and tactile displays can enhance recognition by using non-visual channels of cognition to “get through to” the unaware pilot. Since SD is often triggered by a disparity between visual and vestibular senses, it is wise to stimulate other senses to aid recognition. Audio is an especially compelling input because it tends to override other senses for attention.[10] In addition, we can also consider *verbal* auditory information, such as commands to the pilot on how a control should be moved, or what instruments should be consulted, in order to restore spatial orientation. These too are capable of exploiting the multiple perceptual resources of a visually overloaded (or incapacitated) pilot.

Visual and tactile display enhancements may be less effective during G-induced SD because of vision tunneling and somatic G-force effects.[47] Researchers must also consider how to integrate new display ideas with existing cockpit displays, audio, etc. The goal is to use the “best” sensory cues for the particular SD conditions, if the event characteristics can be confidently established.

In summary, it would appear that a number of features in both visual and non-visual displays can support the pilots’ perception of attitude. For visual displays, many of these capitalize upon ambient vision and the presentation of attitude across a wide range of visual angles. For non-visual displays, they exploit the multiple sensory resources of the pilot. Given other findings in the research literature supporting the advantage of redundant presentations of information,[31] it would appear that offering attitude information through redundant channels could be a valuable tool to restoring spatial orientation. In the following section, we suggest ways in which redundant orientation information can be intelligently accomplished.

Intelligent onboard systems that can recognize SD and its causes would provide an advantage in the fight against negative SD consequences. Such systems would not only tailor displays to the particular SD event, but could trigger recovery actions via synthetic speech to talk the pilot through the appropriate recovery. Such techniques have shown utility in AFRL simulator experiments, and pilots have favorable opinions of the technology. An intelligent system could also initiate recovery without jeopardizing the mission by considering such factors as position relative to enemy airspace, threat warning system inputs, and fire control modes. Triggering an auto-recovery without considering mission impact and pilot intent is unacceptable, except in the most extreme circumstances. Auto-recovery exists on the Swedish Grippen in the form of auto-GCAS.[52] However, US pilots distrust auto-recovery systems due to potential errors and the possibility of adversely affecting the mission. Because of these drawbacks, a pilot-activated system could be an interim step between the present lack of auto-recovery systems in US aircraft and fully-automated ones. However, a pilot-activated recovery system would not be effective for unrecognized or incapacitating SD. Manual activation could be effective for recognized SD events and so should be a part of the layered solution, at least until its efficacy can be proved or disproved.

Extensive research has been done on aircraft state, pilot intent, and hazard monitoring intelligent systems. Such systems would be relatively easier to implement for civilian than for military aircraft, and so can be developed, tested, and certified in the more benign civil environment as a prelude to military systems, if warranted. An intelligent cockpit system could trigger the SD countermeasure(s) determined to be most effective in any given situation. Due to the likelihood of sensory overload, an intelligent SOAS would apply multisensory countermeasures for redundancy, urgency, and for improving the odds of "getting through to" the pilot. We have already discussed visual, auditory, and tactile displays; one other sensory channel remains: olfactory. An intelligent system could trigger a unique harmless odor (similar to a unique audio tone) that means, "Spatial Disorientation strongly suspected; check your instruments!" For incapacitated or unconscious pilots, an odor similar to smelling salts could help the pilot regain consciousness and control.

All the old and new technologies to combat SD incidents have uncertain effectiveness, unless a thorough data gathering and analysis effort is begun. The goal should be to better understand and characterize SD events, and to determine the efficacy of the various SD mitigation tools. Only with *post hoc* analyses will researchers have an objective method to assess the most effective spatial orientation enhancing, or SD prevention and recovery, techniques.[14] Also, an operational analysis system provides the feedback and statistics needed to verify and validate laboratory research results. Lastly, data analyses provide an objective foundation for developing and testing human performance models, such as the multisensory models described below.

Recent post-flight data analysis efforts in worldwide commercial aviation have paid huge dividends in understanding the impact of changes to such key flight safety components as airplane systems, pilot training, air traffic control procedures, and airport conditions. The US Air Force has recently begun such a flight data monitoring program for its C-17s. The value of regular consistent objective feedback is enormous, as global aviation data analysis and sharing programs attest. An analogous effort for SD research is absolutely vital.

There are many known SD illusions and causes. How to best combat each one is the challenge of attitude awareness and SD researchers. The best solution is to blend all of the known helpful training, technologies, and techniques, and to tailor each to the particular SD circumstances. Researchers are investigating a wide variety of technologies. Visual components include head-down, head-up, and helmet-mounted displays. Audio components include 3D audio tones and verbal recovery commands. Tactile components include vibrating vests. Olfactory cues might be useful when the pilots' other senses are overloaded, or when pilots are incapacitated. Training includes classroom lectures, centrifuge demonstrations, and practice flights. Post-flight data analyses provide feedback about which techniques are the most effective under the widely varying conditions of military aviation.

Modeling

The goal of modeling attitude awareness, spatial disorientation, and multisensory workload is to provide a framework for assessing or inferring, in real time, the pilot's level of awareness of the current aircraft orientation, and then, based upon this assessment, implementing an appropriate set of interventions to counter any assessed spatial disorientation events **and** their consequences. Because attention mismanagement (i.e., distraction) is a key component in many SD mishaps, we now turn to modeling the pilot's attention in the form of a multisensory workload measure, SAVVOY, that expands upon Wickens' Multiple Resource Theory.[53]

Wickens' multiple resource theory (MRT)[53] says to use the maximum number of different sensory resources or channels to "get through" any distractions. Since our goal is a multisensory approach to combating SD and since Wickens' MRT focuses on visual and auditory channels, we have expanded MRT to include somatic, vestibular, and olfactory senses. The resulting workload model, which we call SAVVOY (somatic, auditory, visual, vestibular, olfactory, psychomotor-primary, psychomotor-secondary, and cognitive), is useful for helping our Spatial Orientation Aiding System (described later) determine which countermeasures to apply under varying conditions. For example, if the pilot is in a high G maneuver, tactile cues are less likely to be detected by the pilot due to "high somatic workload." Similarly, if the pilot is talking on the radio, audio cues may be ineffective due to high audio workload. For psychomotor, we have primary and secondary observable actions. Primary actions are the pilot's flight control actions. Secondary actions are everything else (such as pushing buttons or turning knobs). We also infer cognitive effort to complete the model of pilot workload.

Two models of SD were developed to detect the occurrence of the Leans and Coriolis illusions – one model for each illusion. Each model uses observable data from the aircraft and pilot to assess the state of the vestibular system relative to the actual attitude of the aircraft.

The model of the Leans is expressed as a timed sequence of events, with the certainty of the assessment of the disorientation increasing with each successive event, as shown in Figure 3. The first event is the initiation of a roll at a rate below the vestibular threshold (Mulder's constant of 2º/sec). The second event is a roll angle of greater than 5º that lasts longer than 5 seconds. If these two events occur in sequence, it is possible that the pilot has not noticed the ensuing roll angle and that there is a difference between the pilot's perceived attitude and the true attitude of the aircraft. As such, the model indicates a *possibility* of SD but only at a very low confidence level. The third event is the loss of altitude as measured by negative vertical velocity. If this event follows the first two, it is possible that the pilot has also not noticed the loss of altitude and the model represents an increased confidence in its assessment of the Leans

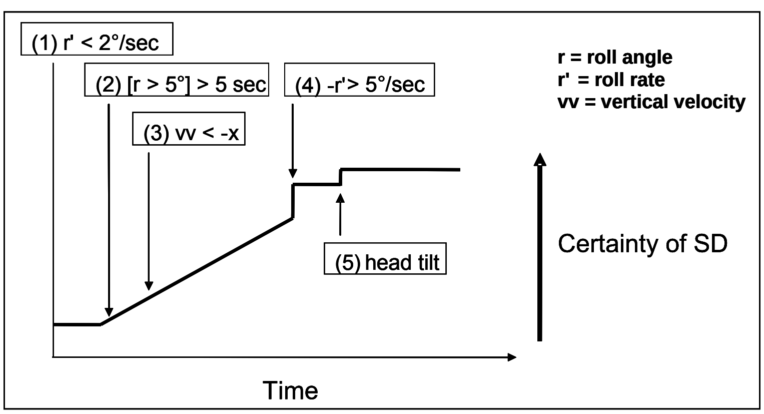

Figure 3. Leans model.

(shown as increasing certainty of SD in Figure 3). The fourth event is a roll well above the vestibular threshold (e.g., greater than 5º/sec and with sufficient duration) in the opposite direction from that of the first event. If this occurs following the first three events, it is possible that the pilot has now noticed the roll angle and has quickly corrected back toward level flight. When this occurs, the pilot's vestibular system will register a roll in the opposite direction, again resulting in a difference between the perceived attitude and the actual attitude of the aircraft. At this point the model represents a high level of SD certainty. The final event in the model is the tilt of the pilot's head opposite the perceived roll angle. If this occurs following the other four events, it is very likely that the pilot is experiencing the Leans and the model represents an even higher level of SD certainty.

Unlike the Leans, the model of the Coriolis illusion is not expressed as a sequence of events but as an instantaneous occurrence. The model is expressed by the maneuvering of the aircraft relative to the movements of the pilot's head in the three different planes (yaw, pitch, and roll). The first event is the aircraft maneuvering such that the rate of change in any of the three planes is above the vestibular threshold (Mulder's constant). If during this maneuvering the pilot's head moves greater than 30º from center in either of the other two planes, then there is the potential for the Coriolis illusion to occur. For example, Coriolis is likely to occur if the aircraft is in an above threshold roll during which the pilot's head moves a large amount (we used 30º) in either the yaw or pitch planes. Since the Coriolis model is based on an instantaneous occurrence, there is no representation of SD certainty or confidence level. Rather, the model simply indicates whether or not Coriolis may be occurring.

"All models are wrong, but some are useful."[54]

At this stage of our research and development, the most important benefit from modeling is a deeper and more thorough understanding of the problem being modeled. In starting with a theoretical approach, we ensured that we considered all of the relevant aspects of attitude awareness and spatial disorientation. Going from the theoretical to what we could practically accomplish with realistic aircraft and state parameters meant that we could prove the feasibility of our approach while remaining cognizant of enhancements to be made in follow-on research.

The importance of effectively combating SD along the whole range of operational exposure is absolutely critical to reducing the human and aircraft costs of this major flying problem and accident causal factor. Clearly, it is much less expensive to combat SD than to replace pilots and aircraft. The time is ripe to apply prevention and countermeasure strategies to SD via pilot selection, training, mission briefings, intelligent cockpit aiding systems, and rigorous post-event analyses. The following section describes how we put all of the previous knowledge together into a prototype SOAS for pilots.

Spatial Orientation Aiding System (SOAS) Prototype

The overall goal of the Spatial Orientation Aiding System is to achieve a multisensory approach to solving SD problems. The system integrates simulated multisensory displays to help pilots recognize and recover from SD situations. The SOAS prototype demonstrates what could be done in either a simulator or target aircraft to alert pilots to an SD situation, and to help them recover.

SOAS consists of three components (Figure 4). The first component is the State Table. It contains state data for the pilot, aircraft, and external world, which it uses to analyze the current state of the aircraft, world, and pilot's level of SD (if any) and multisensory workload. There is also the Countermeasure Assessor, which uses the output from the State Table's assessors to determine the most effective countermeasures for the specific SD situation. Once the

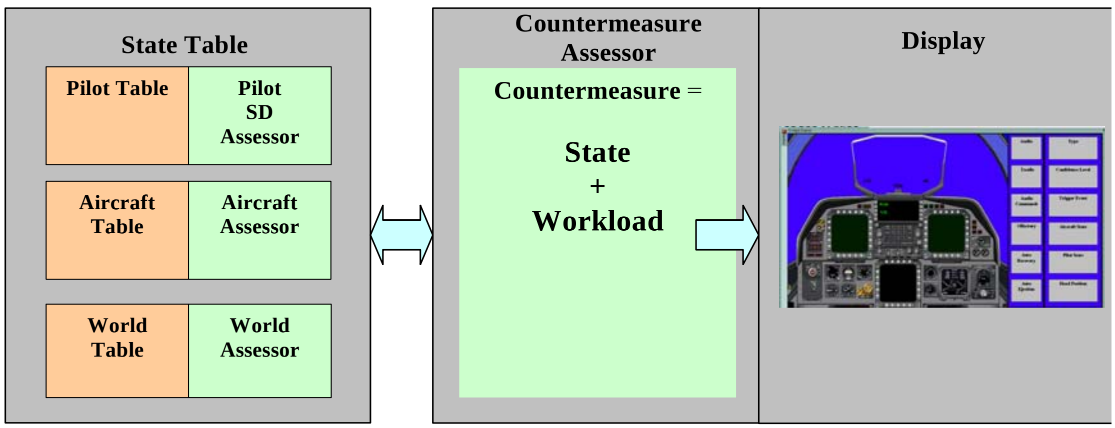

Figure 4. Spatial Orientation Aiding System (SOAS) architecture.

countermeasures are decided upon, the appropriate display(s) are activated. As an SD situation evolves, the State Table's assessors continue to assess the state of the pilot, aircraft, and world. When the situation changes, it informs the Countermeasure Assessor, so that the compensatory actions can be changed accordingly.

The State Table helps SOAS create a complete picture of the pilot's current situation and serves as a communication object among the various processes. To create this picture, the system must know something about the aircraft, pilot, and the external factors (i.e., world) that are influencing the pilot's decisions and physiology. The first piece of this picture is the aircraft for which *raw* data are provided by the aircraft systems (or model, in the case of a simulated aircraft). For instance, the aiding system uses pitch, bank, and airspeed to analyze the motion and position of the aircraft. These raw data are also used to derive parameters such as pitch rate, roll rate, and change of airspeed. Both raw and derived data are stored in the State Table.

The second piece of the picture is the pilot. SOAS must assess the current state of the pilot before it can determine the extent to which the pilot is disoriented. The pilot's state also helps determine the best compensatory actions. For instance, it is important for the aiding system to be able to determine whether or not the pilot is incapacitated. To do this, the aiding tool could use sensors to measure the pilot's heartbeat rate, skin temperature, pupil dilation and other physiological measures of stress and incapacitation. These pieces of raw physiological data along with the derived data are stored in the Pilot State Table (Table 1).

Table 1. Pilot state parameters

Parameter	Range
Head position pitch	-90-+90
Head position roll	-90-+90
Head position yaw	-120-+120
Somatic workload	0-7
Auditory workload	0-7
Vestibular workload	0-7
Visual workload	0-7
Olfactory workload	0-7
Psychomotor primary workload	0-7
Psychomotor secondary workload	0-7
Cognitive workload	0-7

The last data set needed to finish the picture of the pilot's situation is the state of the external world. These data are important because external events can increase the probability of spatial disorientation, and influence how pilots should attempt to recover from their disorientation. Examples of raw data are the presence of threats, time of day, visibility, and latitude/longitude. These data can be used to determine if the pilot is in combat, whether it is day or night, and the type of terrain over which the pilot is flying.

Since there is no "horizon visible" sensor on any aircraft of which we are aware, we can use pilot head tilt angle to give our aiding system an indication of pilot state and orientation with the visible horizon. If the aircraft is banked and the pilot's head position indicates an opto-kinetic cervical reflex (OKCR), then we can assume that the horizon is visible. A lack of OKCR may indicate that there is no visible horizon. In any event, pilot head position is important to our modeling and countermeasures aiding because it is part of the assessment of pilot susceptibility to SD (especially Coriolis).

For our proof-of-concept demonstration, the simulation was used in a deterministic mode in which the time periods and state values for each event did not vary across different model executions. This allowed us to repeatedly simulate exactly the same disorientation sequence in order to evaluate the proper execution of the rest of SOAS. The simulation could also be executed stochastically such that the time and state values would vary pseudo-randomly within some distribution. This would allow the model to represent variations to the original scenarios to help determine the sensitivity and accuracy of our SD illusion models.

The model also includes SAVVOY workload score calculations. These workload scores are stored in the State Table and used by the Countermeasure Assessor to determine the potential effectiveness of different compensatory actions in a specific SD situation.

Once the State Table is filled, SOAS uses this information to determine the extent to which the pilot is experiencing spatial disorientation and the best way to help the pilot recover. The assessors, which are part of the State Table, do the first part of this task. They determine the extent to which the pilot is spatially disoriented and the risk surrounding the current situation. These different assessors within the State Table will be referred to as the State Assessor in the rest of this description of the SOAS prototype. The Countermeasure Assessor determines the appropriate compensatory actions, based on the outputs of the State Assessor.

Since the Leans model is based on a sequence of SD triggering events, the State Assessor keeps track of which events have occurred within the sequence. In addition, it must determine if trigger events that have already occurred are still valid. Each time the State Table is updated, the Leans Assessor begins by looking for a roll rate that the vestibular system does not notice using the axis acceleration multiplied by its duration being below Mulder's constant. For the next State Table update, it first checks that any maneuvers have exceeded Mulder's constant. If Mulder's constant is exceeded (i.e., the motion is detected), the Leans Assessor resets the first trigger and starts over again. But, if Mulder's is still not exceeded, the Leans Assessor then looks for a roll angle of greater than 5 degrees. As the scenario continues, if the pilot's vestibular system is still not reacting based on the Mulder's calculation and the roll angle stays at greater than 5 degrees for greater than 5 seconds, the assessor will determine that a Leans SD has begun and will inform the rest of the system that a Leans is occurring with a low level of confidence. If these conditions continue, the assessor will check to see if the aircraft is losing altitude. If it is, then the assessor will increase the confidence level to medium. If these conditions continue, the assessor will look for an opposite roll *above* the threshold of the vestibular system. If this occurs, the assessor will increase the SD confidence level to high. Finally, if all these conditions have occurred in sequence and the pilot's head tilts in the opposite direction from the roll back, the SD confidence level is increased to very high.

When an SD event has been detected, the system must determine the severity of the pilot's situation. The importance of SD severity can be seen in the SD *remediation network* (Figure 5). The network implies that an increasing severity of SD warrants an increasing level of aiding. This is where the other components of the State Assessor become important. The Aircraft and World Assessors help the State Assessor estimate the severity of the pilot's situation by analyzing aircraft and world state data. SD events can be divided into three primary levels of severity, where each level infers the goal of SOAS.

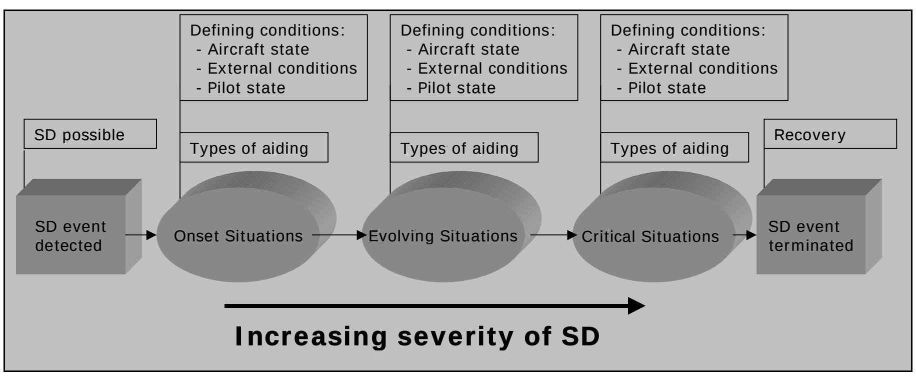

Figure 5. SD remediation network.

These levels are:

1. Onset situations: Emphasis on prevention (Figure 6)
2. Evolving situations: Emphasis on helping the pilot recognize and recover
3. Critical situations: Emphasis on recovery

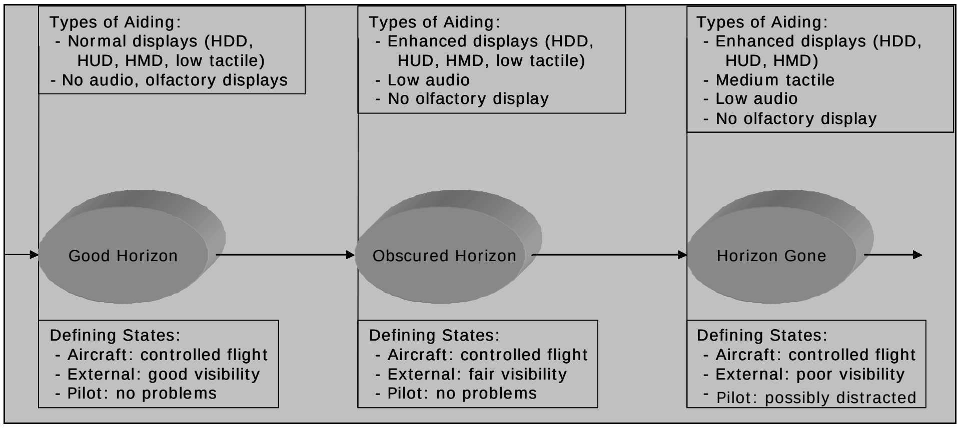

Figure 6. SD Onset remediation network.

The Aircraft Assessor monitors the aircraft's state. Its primary goal is to estimate the situation's current risk based on the aircraft's acceleration and position. For instance, the pilot is in a more severe situation if the aircraft is in an unusual attitude and about to crash, and this assessor monitors the air-craft's time until impact with the terrain. The less time the pilot has to recognize and recover from SD, the more intrusive the countermeasures must be.

The World Assessor monitors the external world's state. In particular, it is concerned with factors that contribute to or increase the pilot's vulnerability to SD. These factors include visibility (Is the horizon visible?), and the presence of enemy threats. One example is that pilots are more susceptible to SD if they cannot see the real horizon. Another example is that we may suspend counter-measure actions if the pilot is jinking to avoid an enemy missile.

These types of calculations are difficult to do because the required parameters are hard to measure with the technology that is currently available in an aircraft. We do not perform calculations in the SOAS prototype that we are not able to do with data provided by a real simulator or aircraft. Consequently, the analyses that occur in this portion of State Assessor are conservative. These concepts are included in our design to ensure completeness. The Countermeasure Assessor uses the SD type and level from the State Assessor to determine what type of cues are appropriate countermeasures. It also uses SAVVOY workload levels from the State Table to determine the predicted effectiveness of each countermeasure. Once the Countermeasure Assessor has selected appropriate countermeasures for the SD situation, it sends this information to the (simulated) aircraft displays. The State Table also stores which countermeasures are presently being used, so that the State Assessor knows which pilot resources are being loaded.

If the State Assessor detects a change in the current SD event, it alerts the Countermeasure Assessor of this change. For instance, if the State Assessor estimates that the pilot has fully recovered from the SD event, it passes this information to the Countermeasure Assessor. Upon receiving this information, the Countermeasure Assessor terminates the various countermeasures it initiated. The State Assessor also informs the Countermeasure Assessor when the SD situation has either decreased or increased in severity, so that the countermeasures can be changed accordingly.

The prototype's Countermeasures represent technologies currently available in a cockpit, such as helmet-mounted displays, as well as new technologies, such as tactile vests. The Countermeasures are represented in a simplified cockpit image (Figure 7) for proof-of-concept demonstration purposes.

Figure 7. Demonstration screen shows multisensory countermeasures and assessor outputs.

Our SOAS prototype builds upon prior intelligent cockpit systems, so we have confidence that the design is robust and suitable for a range of applications, including, spatial disorientation. Our demonstration, which includes the two illusions described earlier, plus a scenario based upon actual data obtained from the Air Force Safety Center proves the feasibility of our model-based concept and approach.

Conclusions

For this proof-of-concept research, we accomplished the following major objectives:

- We performed a literature search, including Russian literature, which formed the foundation of our quantitative, model-based approach.
- We designed and developed models for the Leans and Coriolis illusions. The Leans model worked with the actual F-16 data that we received from the Air Force Safety Center (AFSC) within the last weeks of this project's technical work. We are especially delighted that our SOAS is robust enough to work with this data set in a sensible, realistic manner. (For the actual SD flight data, given to us by AFSC, we took the raw data parameters that we needed, and added small random numbers for other parameters not found in that data set. Then, we ran the data through our SOAS looking for a Leans-like event. We did not try our Coriolis model on the actual data because we did not have pilot head position data. Even without head position data, our Leans model worked because the 5th step in Figure 3, a head tilt, only increases our confidence level; it is not required for a Leans assessment.)

- We enhanced Wickens' Multiple Resource Theory[53] to account for the other senses critical to this effort. We called the resulting "theory" SAVVOY in honor of Dr. Wickens' location in Savoy, Illinois (at the University of Illinois' Aviation Research Laboratory). The newly included senses are somatic, vestibular, and olfactory. A model of pilot workload, using hypothetical (but realistic) SAVVOY scores, influenced the SD countermeasures applied by our SOAS.
- We invented an SD icon (Figure 2) to be an intuitive representation of the aircraft pitch and roll. How intuitive it actually is remains to be seen via testing in ongoing research.
- Most importantly, we delivered a working SOAS prototype that serves as an excellent foundation for follow-on research, development, and testing with pilots in a motion-based simulator, and in flight tests.

The anticipated benefits of this research and development are to help pilots maintain spatial orientation in flight, or, when orientation degrades, to recognize and recover from spatially disorienting situations, thus preventing SD's negative consequences. The cost impact of SD on the US military is over $300 million per year, not counting lives lost. US civilian losses are comparable. Devising a layered approach to even incrementally improve the situation has a multi-million dollar per year potential benefit.

Acknowledgments

The authors gratefully thank the following individuals without whom our work would have been less complete: Mr. Richard Moss and Dr. Kristen Liggett of AFRL provided advice and encouragement; Mr. Bill Ercoline pointed us to the salient contributions in the vast body of SD literature; Dr. Brian Self reminded us of how the various visual-vestibular conflicts actually feel; Mr. Everett Smith and Mr. Jeff Barnette, Air Force Safety Center, provided us with flight data from an actual SD event. The work reported was performed under USAF contract FA8650-04-C-6457.

References

[1] Heinle, T.E. (2001). Spatial disorientation research. In *HSIAC Gateway, 12*(3), 1-3.

[2] Davenport, C. (2000). *Spatial disorientation: The USAF experience, FY1991-FY2000: How much are we willing to pay*? San Antonio, TX: Spatial Disorientation Symposium. At http://www.spatiald.wpafb.af.mil/Mishap%20Studies/Davenport. pdf

[3] Veronneau, S.J.H. (2000). *Civilian spatial disorientation mishap experience*. San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/Mishap%20Studies/Veronnenau.pdf.

[4] Previc, F.H., & Ercoline, W.R. (2001). Trends in spatial disorientation research. *Aviation Space and Environmental Medicine, 72*(11), 1048-1050.

[5] Previc, F.H., & Ercoline, W.R. (2004) (Eds.). Spatial disorientation in aviation (ISBN 1-56347-654-1). Reston, VA: AIAA.

[6] Braithwaite, M.G. (1997). The British Army Air Corps in-flight spatial disorientation demonstration sortie. *Aviation, Space, and Environmental Medicine, 68* (4), 342-345.

[7] Gallimore, J.J. & Liggett, K.K. (2000). *Implications of spatial sensory reflex research on primary flight display design*. San Antonio, TX: Spatial Disorientation Symposium.

[8] Cheung, R. (2000). *Non-visual spatial orientation mechanisms*. San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/MechanismsStudies/cheung.pdf

[9] DeHart, R.L., & Davis, J.R. (eds.) (2002). Fundamentals of aerospace medicine (3rd ed., ISBN 0-7817-2898-3). New York: Lippincott Williams & Wilkins.

[10] Wickens, C.D. (2002). Situation awareness and workload in aviation. *Current Directions in Psychological Science, 11*(4), 128-133.

[11] Holmes, S.R., Bunting, A., Brown, D.L., Hiatt, K.L., Braithwaite, M.G., & Harrigan, M.J. (2003). Survey of spatial disorientation in military pilots and navigators. *Aviation, Space, and Environmental Medicine, 74*(9), 957-965.

[12] McGrath, B.J. (2000). *Tactile instrument for aviation* (Naval Aerospace Medical Research Laboratory Monograph 49). Pensacola, FL: NAMRL.

[13] Lyons, T.J., Ercoline, W.R., Freeman, J.E., & Gillingham, K.K. (1993). Epidemiology of United States Air Force spatial disorientation accidents: 1990-1991. In *Aircraft accidents: Trends in aerospace medicine investigation techniques* (AGARD CP 532:31-1 to 31-11). Neuilly Sur Seine, France: Advisory Group for Aerospace Research and Development.

[14] Lyons, T.J., Ercoline, W.R., Freeman, J.E., & Gillingham, K.K. (1994). Classification problems of U.S. Air Force spatial disorientation accidents, 1989-91. *Aviation, Space, and Environmental Medicine, 65*, 147-152.

[15] Benson, A.J. (1988). Motion sickness & spatial disorientation. In J. Ernsting & P. King (Eds.), *Aviation Medicine*. London: Buttersworth, 318-493.

[16] Gillingham, K.K., & Previc, F.H. (1993). *Spatial orientation in flight* (AL-TR-1993-0022). Wright-Patterson AFB, OH: Air Force Armstrong Laboratories.

[17] ASA (1995). *Federal aviation regulations & airman's information manual* (ISBN 1-56027-204-X). Renton, WA: Aviation Supplies & Academics.

[18] Sipes, W.E., & Lessard, C.S. (1999). Spatial disorientation: A survey of incidence. In R.S. Jensen, B. Cox, J.D. Callister, & R. Lavis (Eds.), *Proceedings of the Tenth International Symposium on Aviation Psychology*. Columbus, OH: Ohio State Univ.

[19] Pines, M. (2003). The mystery of smell: The vivid world of odors. In *Seeing, hearing, and smelling the world* (report from the Howard Hughes Medical Institute). Found at http://www. hhmi.org/senses/ d110.html.

[20] Gopher,D., Weil,M., & Barakeit,T. (1994). Transfer of skill from a computer game to flight. *Human Factors, 36*, 387-405.

[21] Gomez, G. (2002). Spatial Disorientation: Something old & something new. In *Essays & Articles*. Found with Google search at: http://www.isamindia.org/essays/cme_spatial.shtml.

[22] Berkley, W.E., & Martin, E.L. (2000). *Spatial disorientation in night vision goggle operations*. San Antonio, TX: Spatial Disorientation Symposium. Found at: http://www.spatiald.wpafb.af.mil/Primary%20Flight%20Displays/berkley.pdf.

[23] Wickens, C.D., Sandry, D., & Vidulich, M.I. (1983). Compatibility and resource competition between modalities of input, central processing, and output: Testing a model of complex task performance. *Human Factors, 25*, 227-228.

[24] Previc, F.H., & Ercoline, W.R. (1999). The "outside-in" attitude display concept revisited. *The International Journal of Aviation Psychology, 9*(4), 377-401.

[25] Meehan, J.W. (2001). Advanced display technologies: What have we lost? *HSIAC Gateway 12*(3), 13-14.

[26] Bainbridge, L. (1999). Processes underlying human performance. In D.J.Garland, J.A.Wise, & V.D.Hopkin (Eds.), *Handbook of Aviation Human Factors.* Mahwah, NJ: Lawrence Erlbaum Associates, 107-171.

[27] ISO (International Standards Organization) (2002). *ISO 14915-3:2002(E), Annex D: Design issues and cognitive background*.

[28] Ercoline, W.R. (1998). In *Minutes of the 22nd meeting of the DoD flight symbology working group*. Moffett Field, CA: NASA Ames Research Center.

[29] Weinstein, L., & Wickens, C.D. (1992). Use of nontraditional flight displays for the reduction of central visual overload in the cockpit. *International Journal of Aviation Psychology, 2*(2), 121-142.

[30] Previc, F. H. (1998). The neuropsychology of 3-D space. *Psychological Bulletin, 124*, 123-164.

[31] Wickens, C.D., & Hollands, J.G. (2000). *Engineering Psychology and Human Performance*. Upper Saddle River, NJ: Prentice Hall.

[32] Wickens,C.D. (2003). Aviation displays. In P.Tsang & M.Vidulich (Eds.), *Principles and practices of aviation psychology*. Mahwah, NJ: Lawrence Erlbaum, 147-199.

[33] Nelson,W.T., Hettinger,L.J., Cunningham,J.A., Brickman,B.J., Haas,M.W., & McKinley,R.L. (1998). Effects of localized auditory information on visual target detection performance using a helmet mounted display. *Human Factors, 40*, 452-460.

[34] Begault, D.R., & Pittman, M.T. (1996). Three-dimensional audio versus head down traffic alert and collision avoidance system displays. *International Journal of Aviation Psychology, 6*, 79-93.

[35] Endsley,M.R, & Rosiles,S.A. (1995). Auditory localization for spatial orientation. *Journal of Vestibular Research, 5*(6), 473-85.

[36] Forbes, T.W. (1946). Auditory signals for instrument flying. *Journal of the Aeronautical Sciences*, May, 255-258.

[37] Vinje, E.W., & Pitkin, E.T. (1972). Human operator dynamics for aural compensatory tracking. *IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-2*(4), 504-512.

[38] Costello, R.G. (1976). Continuous compensatory audio manual tracking. In *Proceedings of Twelfth Annual Conference on Manual Control* (NASA TM X-73,170). Moffett Field, CA: Ames Research Center, 406-421.

[39] Wickens, C.D. (1986). The effects of control dynamics on performance. In K.R.Boff, L.Kaufman, & J.P.Thomas (Eds.), *Handbook of Perception and Human Performance (Volume II)*, pages 39.1-39.60. New York: John Wiley & Sons.

[40] Wickens, C.D. (1995). Designing for stress. In J. Driskell & E. Salas (Eds.), *Stress and Human Performance*. Mahwah, NJ: Erlbaum.

[41] Gilson, R.D., Ventola, R.W., & Fenton, R.E. (1975). A kinesthetic-tactual display for stall deterrence. In *Eleventh Annual Conference on Manual Control* (NASA TM X-62,464; under FAA contract DOT-FA74WA-3515). Moffett Field, CA: Ames Research Center, 440-451

[42] Solomonow, M., Lyman, J., & Freedy, A. (1977). Electrotactile two-point discrimination as a function of frequency, body site, laterality, and stimulation codes. *Annals of Biomedical Engineering, 5*, 47-60.

[43] Solomonow, M., Raplee, L., & Lyman, J. (1978). Electrotactile two-point discrimination as a function of frequency, pulse width and pulse time delay. *Annals of Biomedical Engineering, 6*, 117-125.

[44] Kaczmarek,K.A. (2000). Electrotactile adaptation on the abdomen: Preliminary results. *IEEE Transactions on Rehabilitation Engineering, 8*(4), 499-505.

[45] Rupert, A.H. (2000). Tactile situation awareness system: proprioceptive prostheses for sensory deficiencies. *Aviation, Space, and Environmental Medicine, 71*(9), A92-99.

[46] Raj,A.K., Kass,S.J., & Perry,J.F. (2000). Vibrotactile displays for improving spatial awareness. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Santa Monica, CA: Human Factors Society, 181-184.

[47] Rochlis,J.L., & Newman,D.J. (2000). A tactile display for International Space Station (ISS) extravehicular activity (EVA). *Aviation, Space, and Environmental Medicine, 71*, 571-8.

[48] Spence, C. (2002). Multisensory attention and tactile information-processing. *Behavioral Brain Research, 135*, pp. 57-64.

[49] van Erp,J.B.F., Veltman,H.J.A., & van Veen,H.A.H.C. (2003). A tactile cockpit instrument to support altitude control. *Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society*. Santa Monica, CA: HFES, 114-118.

[50] Engineering Acoustics, Inc. (2003). See: http://www.navysbir.brtrc.com/cap/briefingsadmin/ea.asp.

[51] Sklar, A., & Sarter, N. (1999). Good vibrations: Tactile feedback in support of attention allocation and human automation coordination. *Human Factors, 41*, 543-552.

[52] Scott, W.B. (1999). Automatic GCAS: You can't fly any lower. *Aviation Week and Space Technology, 150*(5), 76-80.

[53] Wickens, C.D. (1984). Processing resources in attention. In R. Parasuraman & D.R. Davies (Eds.) *Varieties of attention*. New York: Academic Press, 63-258.

[54] Box, G. (1979). Robustness in the strategy of scientific model building. In R.L.Launer & G.N.Wilkinson (Eds.), *Robustness in Statistics*. St. Louis, MO: Academic Press, 202.

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ABSTRACT

Introduction. Aviation spatial disorientation mishaps remain a concern, especially due to their fatality rate. Some of the most insidious disorientations are due to vestibular stimuli in the absence of visual cues. A category of such disorientations are known as somatogyral illusions. **Methods**. To determine the effects of spin rate and duration on the perception of the somatogyral illusion, we examined the subjective response of pilots and non-pilots to rotation around the yaw axis in a flight simulator, in a manner that would mimic two vestibular illusions found in flight: the washout of the semi-circular canals following sustained turns, and the illusory counter-rotation following return to straight and level flight. Twenty-nine subjects (14 pilots) were seated blindfolded in a flight simulator which accelerated to constant plateau rotation rates of 20, 70, and 120 degrees/sec, and then decelerated to stationarity; plateaus were 10, 20 or 40 seconds. Subjects reported (a) the time when the perception of rotation ceased (i.e., the subjective time until washout was reached), (b) the relative magnitude of the counter-rotation experienced; and, (c) the time until the perception of counter-rotation ceased. Subjects also manipulated a slider to provide a continuous subjective measure of their experience of rotation. **Results**. The two time measures increased with increases in both the duration and magnitude of the spin. The increase in perceived washout time with spin rate was non-linear (geometric). There was an interaction between spin duration and spin rate on the experience of illusory counter-rotation magnitude, such that at low rates, spin duration had no effect, but its effect increased at faster rates. The time constant of adaptation of the semicircular canals was estimated to be 8.3 seconds. **Discussion**. The effects were validated against a model of semicircular canal and cupola adaptation, which predicted the data with high accuracy. Pilots and non-pilots did not differ in their illusory experience.

INTRODUCTION

Spatial disorientation (SD) mishaps remain an enduring concern in aviation. While their number in civilian (general) aviation is not large (1.9% in a recent tabulation), over 90% of those that occur are fatal [16]. Furthermore, their frequency is growing in U.S. military operations, estimated to be between 6 and 21% (depending on branch of service) in one study [8], and being a contributing cause in nearly 38% of U.S. Air Force aviation-related mishaps [13]. The continued incidence and seriousness of SD has prompted researchers to seek new methods to both predict spatial disorientation and to counteract it.

A recent effort [11] developed a model that will predict when a pilot is in danger of becoming disoriented. Aircraft motions are compared to a predictive model that determines if a pilot may experience several known illusions, including the somatogyral illusion, the leans, and the somatogravic illusion [4]. The first of these illusions involves the semicircular canals and yaw rotational motion around the vertical axis. During a sustained turn, the rate of subjective experience of rotation gradually declines below the rate of true rotation, a "washout" of the canals, until eventually a point of subjective stationarity is reached, reflecting the dynamics of the cupola [2, 5]. Then, when sustained rotation is halted (e.g., rolling out of a turn) and straight flight is resumed, an illusory sense of counter-rotation is perceived, again reflecting cupola dynamics. Here again the sense of illusory rotation returns to zero after some decay period. It is this illusory counter-rotation that causes the somatogyral illusion and is a major contributor to the leans, and to occasional extension into a more serious graveyard spiral [4]. Our model [11] captures the joint impact of these two illusions – washout and illusory counter-rotation – as they might characterize a pilot's experience when returning to straight flight after a sustained turn. For the purposes of this study we assumed that the perceptual effect of bank change when rolling out of a turn as insignificant to the overall effect of yaw axis rotation perception. The model incorporates assumptions about vestibular thresholds and rates of washout at different angular velocities (rates of turn) and their durations.

Continued development of the model requires further research and characterization of the semicircular canals at rotation rates that are similar to those experienced in flight, with relatively rapid sustained turns. Prior studies, while examining these dynamics in a quantitative fashion [2, 5, 9] have either used vestibular inputs quite different from those characterized by sustained aircraft turns (e.g., using triangular or short inputs) or have focused only on the illusory counter-rotation phase [9]. Also, these studies have not systematically mapped both initial washout and illusory counter-rotation to a range of values characterizing the turn: both its rate and its duration. This is our goal in the current research.

There are a variety of means of assessing perceived rotation [9]. Psychophysical magnitude estimation [10, 12] requires the subject to offer a single numerical value. Analog devices can be classified into three general categories: (1) direct pointing requires pointing to, or verbalizing, alignment with a fixed perceived landmark (orientation) in the external world [3, 5, 14]; (2) indirect pointing via position control (e.g., matching perceived to controlled position, or perceived to controlled velocity) involves rotating a wheel or crank at a velocity proportional to the perceived body rotation [7, 9]; and, (3) indirect pointing via velocity control involves moving a joystick or slider to a position that corresponds to the perceived rotational velocity [1, 6]. To these explicit subjective psychophysical techniques can be added an implicit biological measure, which indicate the brain's sense of rotation by recording ocular nystagmus [5, 9].

While we employ psychophysical measures here to assess the perceived magnitude and duration of rotation, these are insufficient to capture the continuous decay of perceived rotation related to washout. Direct pointing is awkward and difficult when rotations span beyond about 90 degrees (requiring pointing behind oneself) [5]. Indirect position control is plausible, and found to correlate well with nystagmus measures [9], but can be fatiguing if sustained for long durations. Because data from other tracking domains indicates approximate equivalence between position control and velocity control [15] and because we wished to avoid possible fatigue effects, we chose the velocity control technique whereby slider position indicated the perceived velocity and direction of rotation.

The purpose of the current experiment is to fully understand the dynamics of the yaw semicircular canal as these are exercised in the somatogyral illusion expressed through perception, and experienced in the context of a rotating aircraft simulator, with dynamics characteristic similar to those that might be experienced by pilots in flight. These dynamics were created by a trapezoidal spin profile consisting of a constant acceleration of rotation (corresponding to entering a turn), leading to a constant (plateau) rotation rate (angular velocity or spin), set at one of three levels (20, 70, 120 deg/sec.) and persisting for one of three durations (10, 20, 40 sec.), followed by a constant deceleration (corresponding to exiting the turn by rolling back to straight and level flight), followed finally by a stationary period. The three levels of rotation speed were chosen to span a range from relatively tight, but still normal, turns (20 degrees/sec) to rapid rotation typical of a graveyard spiral (120 deg/sec). The three durations were chosen to span a range that was short, but not so short that the transient acceleration response of the cupola had not yet been completed (10 sec), to sufficiently long (40 sec) to assume that washout will have occurred [5].

During the constant rotation plateau, vestibular washout should be experienced as the rotation rate of semicircular canal fluid reaches the rotation of the skull (and simulator) at which point subjective stationarity should be perceived. During the subsequent deceleration and true stationary period, illusory counter-rotation should be experienced in a direction opposite from the original rotation. The magnitude should be equal to that of the final rate of semicircular canal fluid rotation preceding the deceleration phase; but this illusory rotation too should wash out following prolonged steady state (0 acceleration) conditions as the cupola return to their steady state. Pilots expressed their perception of rotation (whether true or illusory) by (a) sliding a slider to correspond with the degree of perceived rotation, (b) indicating vocally their degree of experience of initial illusory rotation following deceleration from the constant rotation, and (c) indicating the point of perceived stationarity (in both true and illusory rotation) by both a verbal and manual command.

In the 3 (spin plateau duration) x 3 (spin rate during plateau) experimental design, we made the following predictions, with varying degrees of certainty: (1) For a given spin velocity, longer durations will make it more likely that washout will be reached, leading after the spin is halted to both a longer duration illusory rotation and a higher perceived magnitude of that rotation; (2) for a given spin plateau duration, a faster spin will increase the terminal rotation within the semicircular canal (and cupola deflection), thereby also leading to a longer illusory counter-rotation and greater perceived illusory magnitude; and, (3) less certain is whether and how these two independent variables will interact. It is possible, however, to predict that with a slower spin, the semicircular canal will be more likely to have reached washout earlier, and so lengthening the initial spin duration will have less of an effect on the two illusion variables (time and perceived magnitude) than its effect will be with the faster spins. We will examine these predictions with an ANOVA model. A second way to test our predictions is by comparing our data with the predictions made by our vestibular model [11], which makes quantitative assumptions regarding the strengths of washout and illusion buildup, integrating these implications for the prediction of the dependent variables.

Our goals in the experiment were thus: (a) to assess the consistency with which the known dynamics of the semicircular canal would be reflected by vestibular perception in subjects experiencing rotation within a simulator; (b) to assess the consistency with which the dynamics creating washout from true rotation would also create illusory counter-rotation of identical or similar magnitude; (c) to provide an estimate of parameters that could be used in our model [11] for predicting spatial disorientation in real time and to use the model to predict the obtained data; and, a final goal was (d) to compare the extent to which the observed patterns of illusions was modified by flight experience.

METHODS

Twenty-nine subjects, all of whom were cadets between 18 and 23 years of age at the United States Air Force Academy, volunteered for the study. Fourteen of the subjects were qualified glider or small-motor aircraft pilots with over 50 hours logged flight time. The remaining fifteen had little to no flight experience. The study protocol was approved in advance by the Air Force Academy's Institutional Review Board. Each subject provided written informed consent before participating.

All spins were completed in a GAT-II (Environmental Tectonics Corporation, Inc.) three-degree of freedom, motion-based flight simulator with the instrument panels and out-the-window display screen blanked. Each subject experienced a total of 18 different test profiles over two days. Trapezoidal spin profiles were utilized for the study: the GAT-II started at rest, accelerated at a rate of 10 deg/sec^2, maintained a constant angular velocity of 20, 70, or 120 deg/sec, and then decelerated at a rate of 10 deg/sec^2. The plateau durations lasted 10, 20, or 40 seconds. Each of the nine profiles were experienced in both the clockwise and the counterclockwise directions (3 angular rates x 3 plateau durations x 2 directions = 18 trials).

During testing, subjects were blindfolded and placed their heads in a stable headrest within the simulator cab. They were asked to report perceived rotation rates, changes in perceived motion, and cessation of motion. A BIOPAC® TS115 Variable Assessment Transducer or "slider" was used to continuously record perceived rotation rate. The slider had a scale of 0-9, with 4.5 as the starting "no rotation perceived" point. Subjects held the analog slider in their lap with one hand, and controlled the slider with the other. Upon the start of each profile, subjects moved the slider in the direction of perceived rotation until maximum velocity was perceived. The slider position remained stationary if the subjects perceived a constant angular velocity, and upon a perceived deceleration, the subjects moved the slider back towards the middle. If a complete stop was felt (i.e., subjective stationarity), they reported the stop verbally and by tapping a BIOPAC® digital TSD116B foot switch. This point was then used as the new "neutral" or zero position; subjects were not expected to scale their perceptions so that they would return to the 4.5 position on the slider. During the deceleration of the GAT, subjects typically perceived a rotation in the direction opposite from their actual spin. To record this perception, the subject then moved the slider in the direction opposite of their initial input to indicate the magnitude of this perceived counter-rotation. As before, when the illusory motion diminished, they moved the slider back toward the center, and when motion perception stopped, they provided a verbal report of "stop" and tapped the foot switch.

Verbal reports and the foot switch were used concurrently to report two other events. The first report usually involved the shorter duration (10- and 20-second) plateaus when the subjects often did not experience washout and subjective stationarity. During these profiles, perceived rotation could go directly from a left spin to a right spin (or vice versa). In these instances, subjects were instructed to simply report "switch" and tap the foot switch. The other event that was reported was the time when the maximum perceived rotation rate was achieved.

The maximum perceived velocity was measured on a subjective scale of 1 to 10. Subjects were instructed to assign a value of 10 for the magnitude of the maximum velocity in the initial spin direction for each profile. Then, upon reaching the apparent maximum velocity in the alternate direction (i.e., during illusory counter-rotation), subjects were asked to quantify how fast they perceived they were spinning relative to the "10" rating in the initial direction. For example, if they perceived they were spinning half as fast after the switch in direction as they were before the switch, they reported a "5." A review of data integrated by Guedry [5] indicates that with a relatively modest amount of training, subjects are able to accurately reflect the true rate of rotation with such verbal estimates.

For each subject, data collection took place over two separate one-hour sessions with at least 24 hours between each session. The first session began with three training spins along with six experimental spins; the second session consisted of the remaining 12 spins. The subjects rested for at least 60 seconds between each test run. The training run profiles were 20, 70, and 120 deg/sec with 40-second plateaus to familiarize the subjects with the different angular velocities, use of the equipment, and the test methodology. The order of the profiles was randomized using a Latin-square sequence. Subjects encountered two quasi random sequences of the nine profiles. A profile administered in one direction (e.g., clockwise) in the first sequence was subsequently encountered in the other direction in the second sequence. Order was further constrained so that profiles alternated directions to prevent the subject from adaptation during prolonged spinning in one direction. Thus the direction of spin (unlike the magnitude or duration) could always be anticipated. The first sequence of 9 profiles was distributed between day 1 and day 2, while the second sequence was entirely administered on day 2. (However, because of a procedural error, only half the subjects provided data for the 70 deg/sec, 20-sec spin.)

RESULTS

A representative graph from a 70 deg/sec, 40-second plateau trial is shown in Figure 1. The spin profile, the slider data, the verbal responses, and the foot switch inputs are all depicted. From this graph, two major dependent variables were calculated: the time to subjective stationarity (TSS) and the duration of illusory motion (DIM). As reported in Figure 1, the TSS is the time from the beginning of the plateau until the subjects felt they were no longer spinning (an event which did not occur for all profiles, particularly the shorter ones); and the DIM is the time from the cessation of GAT motion until the perceived illusory self-motion ceased.

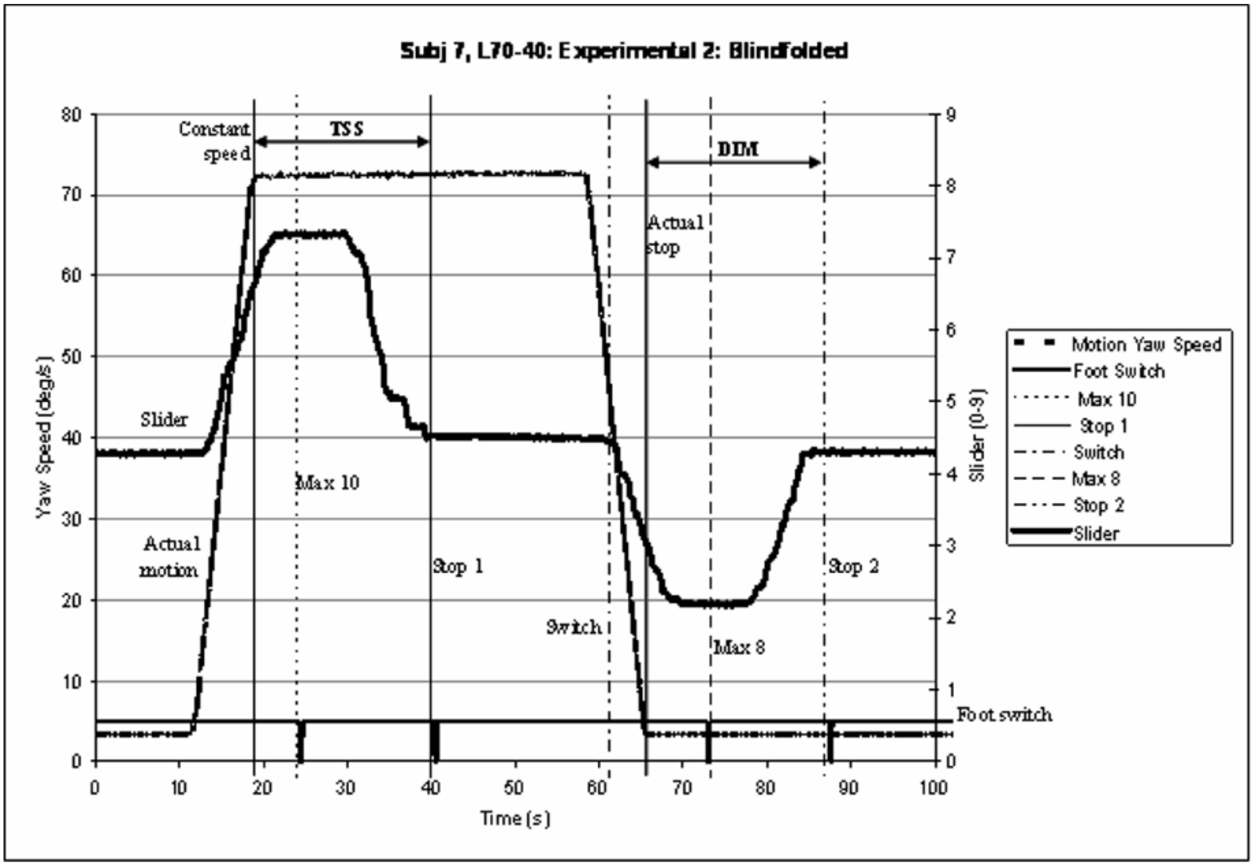

Figure 1. A graph of a counterclockwise (left) spin at 70 degrees/second for 40 seconds. Initial and subsequent max velocities, actual and perceived stopping points, and the switch in direction are marked by vertical lines as indicated in the legend. The TSS is measured from the beginning of the actual profile's plateau to the first perceived stop. DIM, the time from the cessation of actual motion until the perception of rotation in the opposite direction ends is measured from the end of the profile to the second perceived stop.

Figure 2 portrays cumulative slider data from the initial 120 deg/sec, 40-second duration rotation. The separate lines correspond to the slider data for the separate replications of all subjects who generated usable slider data. The figure reveals the general pattern of subjective response in returning the slider toward neutral, along with the degree of variability between subjects of that time course. The model prediction is depicted by the heavy line. Returning to Figure 1, across subjects and trials, both the foot switch and verbal signal appeared at roughly the same time as the slider stop position (e.g., Stop 1 from the TSS in Figure 1 is a typical example). These two discrete signals tended to be more consistent with each other than with the slider return to neutral position, which was not unexpected. The two former signals were therefore averaged in order to estimate, for each subject, on each run, the time point of subjective stationarity (TSS), and therefore the duration of washout. Similar procedures were used to estimate the duration of illusory motion (DIM) during the stationary phase. The two replications for each profile were averaged to provide a single estimate for each subject, which was the input for statistical analysis.

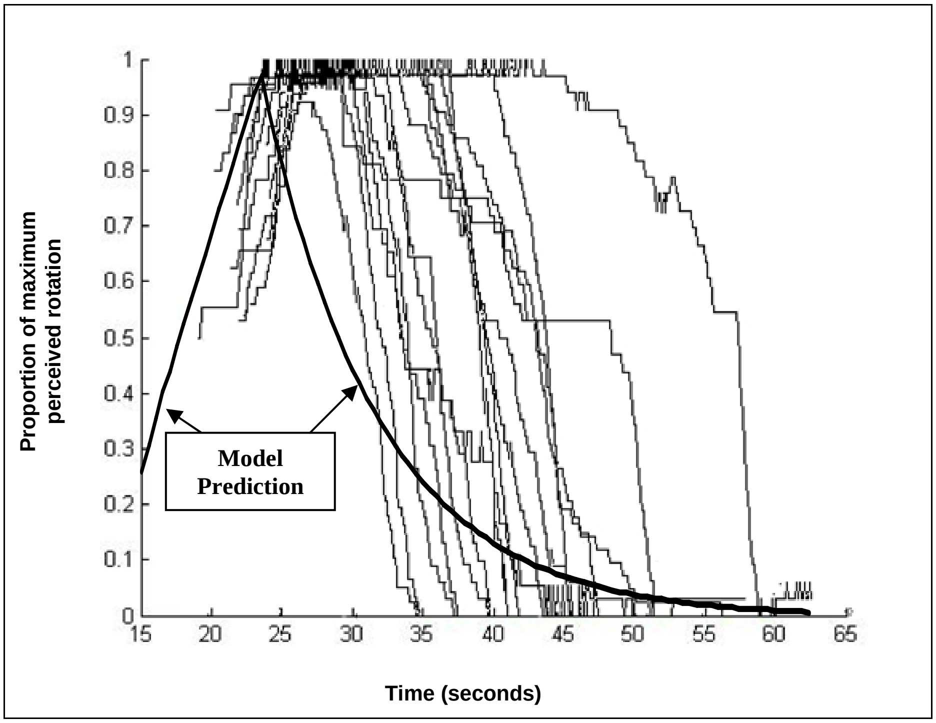

Figure 2. Slider movement for the Left 120 deg/sec, 40-second spin. Data are shown for the 16 subjects who had usable slider data for this particular trial. The heavy line depicts the model [11] prediction.

Three separate 3x3 repeated measures analyses of variance (ANOVAs) were carried out on the three dependent variables of greatest interest: TSS, DIM, and the verbal estimate of subjective magnitude of the illusory rotation. In each ANOVA the two factors were the three levels of spin duration and the three levels of plateau spin velocity. All ANOVAs accounted for missing data (from some subjects on some trials), as the repeated-measures analysis (run using SPSS) is useful for both balanced and unbalanced models. All ANOVAs were accompanied by Huynh-Feldt adjustments for violations of sphericity (when deemed appropriate by Mauchly's test of sphericity), and were corrected where needed.

We note first, that in some cases, some subjects never reported that subjective stationarity had been reached, as described above. Hence the number of observations constituting each of the 9 data points varied. Across the 120 deg/sec conditions, this number is 34, 37 and 38, for 10 sec, 20 sec and 40 sec, respectively. For the 70 deg/sec conditions it is 41, 34 (this condition was the one sampled for only half (14) of the subjects. Seventeen stops were reported for these; thus, we doubled the number to 34 to estimate the number of stop reports we expected had all subjects experienced this condition), and 42. For the 20 deg/sec condition, N is 21, 28, and 40. Thus we notice in several cases, particularly for the shorter and slower spins, a stop signal was not given because subjective stationarity was not perceived before the counter-rotation started.

Figure 3 shows the TSS for the true rotation (signaling the time of complete washout), for those subjects who gave a stop signal, as a function of the three levels of spin rate and the three plateau durations of rotation. An ANOVA reveals the generally monotonic and additive effect of both spin rate ($F [2, 8] = 6.9$, $p < 0.02$) and duration (adjusted for sphericity violation, $F [1.102, 4.41] = 11.5$, $p < 0.05$) on TSS. The interaction between these factors was not significant (F [4, 16] = 2.48, p = 0.11). The effect of spin duration is essentially linear as reflected by the product moment correlation (Yaw 20, r = 0.97; Yaw 70, r = 0.99; Yaw 120, r = 0.99) with significant contrasts between 10 and 20 seconds ($p < 0.01$) and between 20 and 40 seconds ($p < 0.02$). However, the effect of spin rate (yaw velocity) is distinctly non-linear, with a much smaller effect ($p = 0.10$) between the two slower speeds than between the middle and fastest ($p < 0.05$).

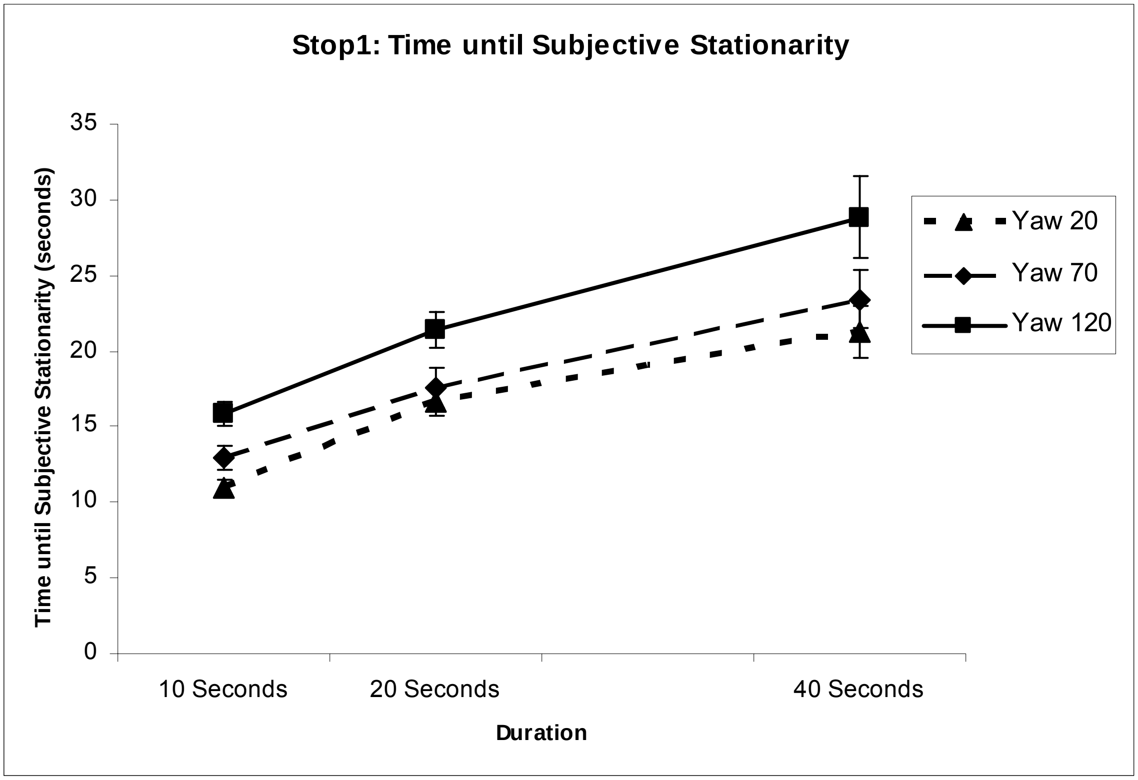

Figure 3. Duration of time until subjective stationarity (TSS). Note that in some cases, some subjects never reported that subjective stationarity had been reached. Hence the number of observations constituting each of the 9 data points varied. Across the Yaw 120 line, this number is 34, 37 and 38, for 10, 20, and 40 seconds respectively. For the Yaw 70 line, it is 41, 34 and 42. For the Yaw 20 line, it is 21, 28 and 40. Error bars represent one standard error above and below the mean.

As was shown in Figures 1 and 2, the form of the decay toward this point of subjective stationarity is slightly ojival, indicating a gradual increase in deceleration perception, followed eventually by a decay toward 0. We estimated the decay constant using only the 40 second spins because only here could we assume that the point of subjective stationarity was consistently reached before the deceleration phase of the profile would contribute a counter-rotation illusion to the perceived magnitude. The estimate of the decay constant from these data was t = 8.3 sec.

Figure 4 depicts the perceived duration of illusory motion (DIM), following the true stationarity of the simulator. In contrast to the data for TSS, nearly all subjects reported the second stop, allowing measurement of DIM. Again, the data reveal monotonic effects of both spin rate (adjusted $F [1.326, 10.606] = 16.78$, $p < 0.01$) and spin duration ($F [2, 16] = 12.80$, $p < 0.01$) with a non-significant interaction effect ($F [4, 32] = 2.48$, $p > 0.05$). Comparisons between adjacent pairs of each dependent variable did not reach conventional levels of statistical significance ($p < 0.05$). Noteworthy is the fact that, while the mean duration of TSS (Figure 3) and illusory rotation (Figure 4) are roughly equivalent, the effect of increasing spin duration (calculated as the difference between the fastest and slowest spin) was considerably greater in the original washout (Figure 3: 10.5 sec) compared to its effect on the later illusory rotation (Figure 4: 5.5 sec). In contrast, the effect of increasing spin rate was close to equivalent across the two measures (original washout: 5.7 sec; illusory washout: 4.3 sec). In order to confirm these observations, the two dependent variables of time estimation (TSS and DIM) were collapsed into a single ANOVA with phase (spin versus stationary) as an added factor. This ANOVA revealed no effect of phase (the duration of illusory rotation was as long as that of true washout), an interaction between phase and spin duration ($F [2, 8] = 13.249$, $p < 0.05$), but no significant interaction between phase and spin rate ($F [2, 8] = 4.383$, $p = 0.052$). Thus the effect of spin duration is diminished from true washout to illusory washout, while the effect of spin rate is not.

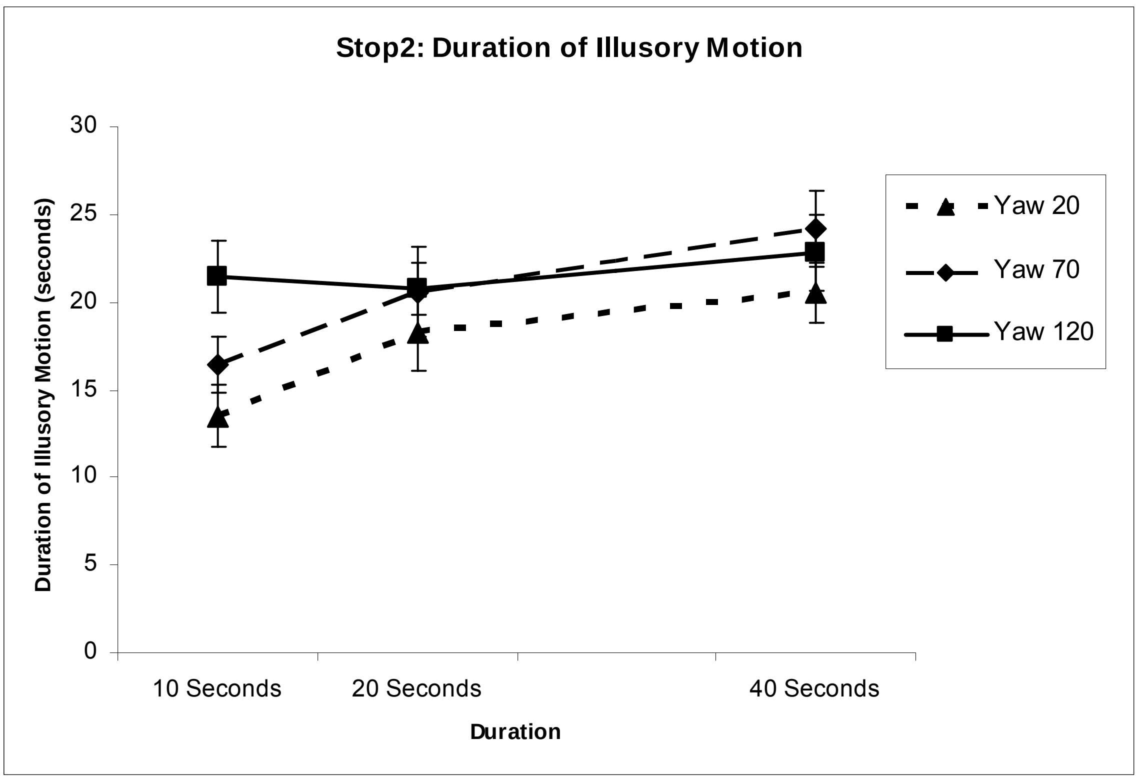

Figure 4. Duration of illusory motion (DIM).
Error bars represent one standard error above and below the mean.

An ANOVA was conducted on the subjective magnitude of the illusory rotation whose data are shown in Figure 5. The ANOVA revealed no effect of duration ($F [2, 18] = 0.48$), nor of spin rate ($F [2, 18] = 0.60$), but a significant effect of spin rate and duration interaction ($F [4, 36] = 2.69$, $p < 0.05$). This interaction reveals that the increasing duration of the initial spin increased illusory magnitude for the two fastest spin rates (and more so for the fastest spin rate, an expected effect), but had no effect on illusion magnitude for the slowest spin. In considering why, at 10 sec duration the Yaw 20 spin produced larger illusory ratings than the faster spins, it is important to recall that these ratings were given relative to relative to the initial (actual) spin, rather than on an absolute scale. Importantly, the overall magnitude of experienced illusory rotation is roughly half that of the initial rotation (M = 5.8 on a scale of 1 to 10, where 10 was assigned to estimate the rate of the initial (actual) spin), and this attenuation factor remains little effected by the original rotation rate.

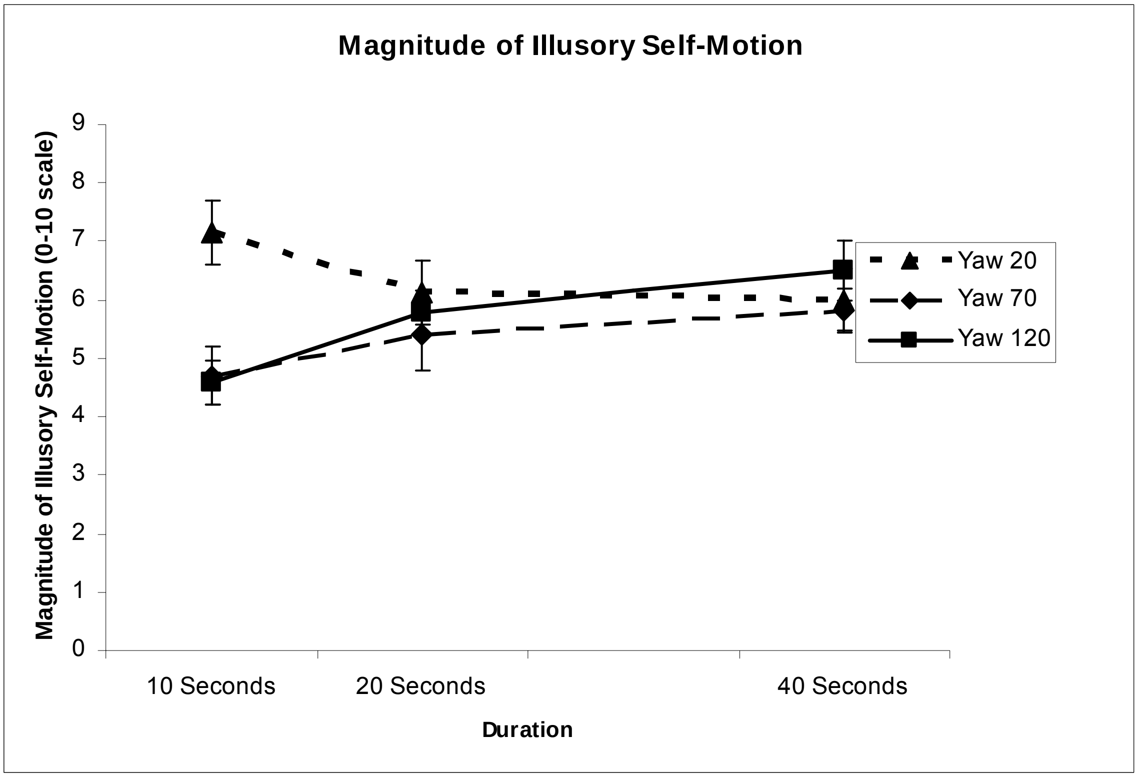

Figure 5. Magnitude of illusory rotation.
Error bars represent one standard error above and below the mean.

Finally, analyses were conducted on the three dependent variables, now dividing the subjects into pilots and non-pilots, thereby creating a third "experience" variable, to be coupled with plateau duration and spin magnitude. Importantly, there was neither a main effect of experience, nor any significant interactions between experience and profile parameters (all p's > 0.10), suggesting that both groups were influenced equivalently by the spin dynamics.

DISCUSSION

The fundamental assumption underlying this research is that two primary parameters will affect the perceived rotations in our subjects: the true rotation of the aircraft, and the time allowed to reach a constant rate of rotation. This speed of semicircular canal fluid rotation, whether it reaches washout (fluid rotation equal to skull rotation) or not, will determine both the magnitude and duration of illusory counter-rotation, once deceleration has begun and true rotation has ceased. In the current data, it is apparent that neither the 10- nor 20-second spin duration allowed asymptote (washout) to be reached. Had it been, then the 40-second duration would have produced no further increase in illusory magnitude, relative to the 20-second duration. So both independent variables that contributed to the faster semicircular canal fluid rotation rate (as assessed by the longer washout estimate) led to a consistently longer counter-rotation illusion. However the spin duration effect on time to subjective stationarity (TSS) declined more from the original rotation (Figure 3) to the illusory rotation (Figure 4) than did the spin rate effect. The linear correlation between the two duration measures (TSS and DIM) was indeed quite high (r = 0.85).

Given the pattern of data shown in Figures 3, 4 and 5, it is appropriate to discuss some of the departures from a linear additive model of spin duration and magnitude that were observed. First, we note the interaction in Figure 5, whereby with low spin rates (the dotted line), increasing spin plateau duration had no effect on illusory magnitude (actually a non-significant decrease), but the plateau duration effect emerged and was progressively greater as rates increased to 70 and then to 120 deg/sec. This effect was predicted, because we assume that the decay or washout from the slow spin (dotted line) was already essentially completed relatively rapidly, so that increasing duration from 10 to 20 to 40 seconds did nothing to increase the sense of counter-rotation. With greater spin rate magnitudes of 70 and 120 deg/sec, however, decay would be less than fully complete after 20 seconds, and particularly after 10 seconds, so that the longer spin durations would allow washout to occur at a faster angular velocity (and thereby increase the magnitude of illusory counter- rotation). It remains somewhat puzzling why this pattern of effects (actually the absence of a duration effect for the slowest spin) was manifest only in the subjective magnitude of the illusion and not the duration. The most noteworthy departure from linearity is the nonlinear effect of spin rate on the initial washout time (Figure 3 TSS), such that only small differences are observed between the two slower rates, but a large increase is observed from the middle to the fastest rate.

The current data also served to address another important goal of the experiment, revealing a fairly consistent estimate of the washout decay time constant (t = 8.3 sec) across spin rates for the longest (40 sec) plateau, within which such a decay could be readily measured in most subjects, as the point of subjective stationarity (complete washout) had been reached. This value suggests a faster rate than that estimated on the basis of nystagmus responses [5, Figure 21]. This parameter has been incorporated into our model [11], as we now discuss.

In order to evaluate the conformance of the current experimental data set with predictions from the computational model of perceived yaw axis velocity [11] which integrates the two illusory phenomena (washout and counter-rotation), parameters of the nine conditions coupled with the best fit 8.3 sec decay constant, were input to the model. The model then generated curves such as that shown in Figure 2, representing the model-predicted “slider data” or subjective perception of rotation. From these curves were extracted the computational measure of illusory magnitude. We wished to correlate these with the subject-generated ratings of illusory magnitude. However the values depicted in Figure 5 are those of <u>relative</u> magnitude, always normalized against the value of 10 that was assigned as the standard for the original rotation, whether this was 20, 70, or 120 deg/sec. Had we instead requested absolute ratings, there is no doubt that the three rotation speed triads would have been offset accordingly, with the “Yaw 20” (20 deg/sec) line in Figure 5 much lower, and the “Yaw 120” line much higher. We estimated the amount of these offsets on the basis of Stevens’ law of psychophysical rotation magnitude estimation, in which an exponent of 1.3 relates perceived to actual magnitude [12]. Applying the correction, in order to create an estimated perceived absolute magnitude (lowering and raising the two lines in the graph by proportionality given by the 1.3 exponent), we correlated these estimated perceived rotation rates, with the model predictions, and observed a correlation of r = +0.966, a strong validation of the success of the model predictions.

We did not attempt to use the model to predict the two time measures, for the reason that such prediction would have required estimating a given threshold at which the model would have reported a "stop". Because such a threshold occurs at a very low level of perceived rotation and therefore at a point at which the decay curve is nearly flat, a very slight change in this threshold (e.g., 4% to 3% of maximum assumed to be the threshold) would cause very large changes in the model-predicted stop time. Since we had no objective way of assessing what threshold value subjects actually used to say "stop", we had little confidence in basing this model on any particular value.

Our final goal was to establish the extent to which some level of flight experience might mitigate or alter the strength of the two phenomena (washout and illusory counter-rotation). Clearly the current data do not support this hypothesis. Despite the relatively high statistical power of the experiment and the consistently observed statistical effects of other variables, the analysis by experience failed to reveal any effects that were even "close" to statistical significance (i.e., using the more liberal criterion of 0.10). Such a finding (although tempered by the fact that we did not include any high-time fighter pilots in our sample) is certainly consistent with the evidence from mishaps and spatial disorientation incident reports, that spatial disorientation problems do not disappear with experienced pilots [8].

In conclusion, the current research sought to understand and quantify two of the illusory effects that are often involved in a pilot's misperception of aircraft state, leading to the leans and eventually to the grave yard spiral. These are the "washout" associated with a sustained rotation, and the illusory counter-rotation when that true rotation has ceased. To this can be added a third illusory component, not examined here, but critical in initiating the first two: that is, the failure of pilots to notice sub-threshold rolls (rotation around the fuselage axis of the airplane), that can initiate the rotation around the vertical axis. Our data were the first to describe both of the first two effects, acting in consort, in a way that would mimic the pilot intentionally trying to come out of a sustained tight turn, and we observed that all 9 conditions generated substantial illusions of both sorts. Importantly, we were also able to predict much of the variance in illusory experience from a fairly simple computational model.

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REFERENCES

[1] Bonato F, Bubka A. Chromaticity, spatial complexity, and the perception of self-motion. Perception 2006; 35:53-64.

[2] Cheung B. Nonvisual illusions in flight. In: Previc FH, Ercoline WR, eds. Spatial disorientation in aviation. Reston, VA: American Institute of Aeronautics and Astronautics; 2004:243-75.

[3] Collins WE. Subjective response and nystagmus following repeated unilateral caloric stimulation. Ann Otol 1965; 74:1034-55.

[4] Gillingham KK, Previc FH. Spatial orientation in flight. Brooks AFB, TX: US Air Force Armstrong Laboratories; 1993. Report No.: AL-TR-1993-0022.

[5] Guedry FE. Psychophysics of vestibular sensation. In: Kornhuber H, ed. Handbook of sensory physiology. Berlin: Springer-Verlag; 1974:3-154.

[6] Guedry FE, Ceran SJ. Derivation of subjective velocity from angular displacement estimates made during prolonged angular acceleration: Adaptation effects. Ft. Knox, KY. US Army Medical Research Laboratory; 1958. Report No. 376.

[7] Guedry FE, Stockwell CW, Norman JW, Owens GG. Use of triangular waveforms of angular velocity in the study of vestibular function. Acta oto-laryng 1971; 71:439-48.

[8] Holmes SR, Bunting A, Brown DL, Hiatt KL, et al. Survey of spatial disorientation in military pilots and navigators. Av Space Env Med 2003; 74(9):957-65.

[9] Okada T, Grunfeld E, Shallo-Hoffmann J, Bronstein AM. Vestibular perception of angular velocity in normal subjects and in patients with congenital nystagmus. Brain 1999; 122(7):1293-1303.

[10] Parsons RD. Magnitude estimates of the oculogyral illusion during and following angular acceleration. J Exp Psych 1970; 84:230-8.

[11] Small RL, Fisher AM, Keller JW, Wickens, CD. A pilot spatial disorientation aiding system. Int Acad Human's Problems Av Cosmonautics Bulletin 2005; 1(17):26-45 and 2(18):28-38.

[12] Stevens SS. The psychophysics of sensory function. Am Scientist 1960; 48:226-53.

[13] Sundstrom JN. Flight conditions leading to Class A spatial disorientation mishaps in U.S. Air Force fighter operations: FY93-02 [Master’s Thesis]. Washington DC: The Department of Preventive Medicine and Biometrics of the Uniformed Services, University of the Health Sciences; 2004.

[14] von Bekesy G. Subjective cupulometry. AMA Arch Otol 1955; 61:16-28.

[15] Wickens CD. Manual control. In: Boff K, Kaufman L, Thomas J, eds. Handbook of perception and human performance. New York: Wiley Interscience; 1986: vol. 2, chapter 40.

[16] Wiegmann D, Faaborg T, Boquet A, Detwiler C, et al. Human error and general aviation accidents: A comprehensive fine-grained analysis using HFACS. Washington DC: Federal Aviation Administration; 2005. Report No. AM-05/24.

Title: Multi-sensory enhancement of command displays for unusual attitude recovery
Running Title: Multi-sensory enhancement
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Abstract

In a low-fidelity fixed-base F-16 flight simulator, 12 fighter pilots attempted to recover from unusual pitch-down inverted attitudes. Recovery was done in a control condition, aided by a HUD only, and with three command display augmentations: (1) a command visual icon, pointing in the direction of appropriate control; (2) the icon augmented with a voice command; and, (3) augmented with a tactile command. All three command displays reduced the time to make the initial recovery response relative to the control condition, and decreased the frequency of initial incorrect roll responses. The tactile and voice augmentations also improved the speed of initial recovery response from the most severe inversions. Although the tactile command effectively supported performance, it was the least preferred of the three display augmentations.

Introduction

Spatial disorientation (SD) continues to be an enduring problem in aviation. For example, during the 1980's and 90's, SD was a factor in approximately 21% of all US Air Force *Class A*[*] mishaps. Between October 1993 and September 2002, there were 25 high performance fighter or attack mishaps where SD was identified as a causal or contributing factor. These mishaps resulted in 19 fatalities and cost the Air Force over $455 million (Sundstrom, 2004). In the United Kingdom, SD mishap frequency is estimated to be between 6 and 21% (depending on branch of service) (Holmes et al., 2003). Furthermore, SD accidents are often fatal. In civilian aviation, Wiegmann et al. (2004) observed that over 90% of SD accidents resulted in fatalities. In the current research we are most directly interested in the loss of attitude awareness (knowing which way is up, and the orientation of key spatial landmarks).

Not surprisingly, along with training (Braithwaite, 2004), research has focused on display changes and augmentations that may prevent SD accidents either by aiding recovery from SD, or by preventing SD from occurring in the first place. Some display approaches focus directly on visual displays. For example debates on the appropriate frame of reference for attitude indicators are based, in part, on the fact that the inside-out moving horizon attitude indicator more readily invites inappropriate corrections when in unusual attitudes (Roscoe, 2004; Kovalenko, 1999; Previc and Ercoline, 2001). Recent advances in visual display augmentations have also focused on incorporation of augmenting visual cues (typically on a HUD) to indicate the direction of the

[*] A Class A mishap is defined as one where there is loss of life, injury resulting in permanent total disability, destruction of an AF aircraft, and/or property damage/loss exceeding $1 million (Air Force, 2001).

horizon (Hawarth and Evans, 2004; Reising, Liggett and Munns, 1999), or to command the direction of stick movement that will restore level flight from an unusual attitude (Wickens et al, in press).

An alternative approach is through **sensory augmentation**, whereby added auditory or tactile information is presented to preserve, or restore, orientation. Such augmented cues have the advantage of supporting perceptual processing even if the visual channel is overloaded, is tunneled on a particular indicator (e.g., the attitude indicator), or is degraded because of high g forces (e.g., Erp, Veltman, & van Veen, 2003, Eriksson et al, 2006).

In considering either auditory or tactile cues, a critically important distinction is between **status** displays, that inform the pilot where the horizon (or some other orientation landmark) currently is, and **command** displays, that inform the pilot of an action to take to restore an appropriate orientation. There are numerous differences in these two display philosophies (Andre and Wickens, 1992; Wickens and Hollands, 2000), many of which are somewhat peripheral to the current issue. However one key difference is that, in time-critical situations, so long as the reliability of the automation-induced action command is high, command displays will be more effective than status displays (Sarter and Schroeder, 2001). This is, in large part, because the command display eliminates a time-consuming and potentially error-prone human decision regarding **what** to do when an inappropriate status (e.g., attitude) exists.

The distinction between status and command displays is also relevant to the distinction between displays designed to prevent SD in the first place (status displays are typically used; e.g., that shows where the horizon actually is), and those designed to recover from existing SD. In the latter case, given the time criticality of the adverse state, command displays are preferable, and hence such command displays represent the focus of the current experiment, comparing visual with auditory and with tactile command displays.

As noted, a visual command display can often be represented as an arrow or pointer commanding an **action**. With an auditory display, the most compatible way of unambiguously representing an action is through voice command (e.g., “pull up”), rather than through auditory spatial cues (e.g., Begault and Wenzel, 1992, Brickman et al, 2000). Voice can directly articulate the verb which signals action, whereas a tone cannot, as it is more ambiguous. Does a tone in the left ear indicate that one should pull to the left, or that danger is on the left (hence pull to the right)? In fact, it may be argued that a verbal auditory command is even less ambiguous than its visual counterpart, the arrow or pointing icon. Indeed, the authors have recordings of two SD incidents where a person outside the incident aircraft helps the incident pilot recover via instructive radio calls.

In contrast to voice, tactile displays are sufficiently new in their airspace implementation that there are no firm guidelines with regard to presenting status or command information. Indeed there appears to be a mixture of display types proposed (Van Erp et al., 2006; Sarter, in press). For example some of the best evaluated systems appear to use tactile status displays (e.g., Rupert, 2000), indicating for example a constant heading, orientation, or gravitational vector, location and severity of wing icing (McGuirl and Sarter, 2001), or automation changes (Sklar and Sarter, 1999). With few exceptions, these have not been compared directly with other non-visual modality displays. A study by Calhoun et al (1993) compared tactile with auditory alerting, as redundant channels with a visual alert, and revealed that both non-visual modalities improved performance equally. A study by Ho & Sarter (2004) found qualitative differences between the three (auditory, visual, tactile) channels as communications media. More recently, van Erp et al. (2006) have directly compared command versus status tactile displays for recovery of constant heading, when spatial orientation is lost due to the effects of the somatogyral illusion (e.g., the feeling of turning following cessation of a constant prolonged turn). In a between-subjects design, they found no difference in effectiveness between these two forms of sensory augmentation, although they found that both were superior to a control condition in terms of their ability to restore straight flight.

Actual comparisons between auditory and tactile command information as deployed in a command mode for unusual attitude recovery do not appear to have been conducted, and such a comparison is the objective of the current study. Here pilots flying a low-fidelity fixed-base F-16 simulator implemented with Microsoft *FlightSim* are diverted into an unusual attitude and then, depending on conditions, requested to recover as rapidly as possible, either (a) unaided (using only the status-based HUD [although augmented as in the real airplane with a pull-up voice command when within a short time of ground impact]), (b) aided by a visual icon alone (pointer in the direction of the necessary control movement(s), (c) aided by voice commands + visual icon and (d) aided by tactile "action" commands + visual icon, whereby the movement of apparent sensation across the torso signaled the direction of required roll (lateral movement) or pitch correction (vertical movement).

Method

Equipment

The equipment consisted of a Dell 3.2 GHz, Pentium 4 processor with a 30" liquid crystal display (LCD) monitor. In addition, a Thrustmaster Cougar stick and throttle was used to simulate the F-16 input devices. Software included Microsoft FlightSim 2004 with an approved F-16 model downloaded from the Microsoft Flight Simulator Developer web site (found at: http://www.lagosim.com/?act=scheda&p=100034&lang=eng&undersearch=fs%20falcon). The vibro-tactile vest was made by TNO, a company in Holland. The vest contains 64 tactors that could be programmed to give specific low-frequency vibration feedback. Voice commands were produced through the computer's sound card and the two front speakers of a six-speaker system. The display/control interface was positioned within a fighter-aircraft cockpit mockup, shown in Figure 1.

Participants

The participants were 12 Air Force pilots all with fighter aircraft experience. All 12 pilots also had over 100 hours of HUD experience.

Task

The pilots' task was to fly a series of legs at a fixed altitude above ground, and respond to the imposition of unusual attitudes by restoring the aircraft to a wings level (within 10 degrees) and pitch level (within 5 degrees) attitude at or above 1000 feet radar altitude and 350 knots (within

10 knots) as rapidly as possible. When the pilot reached these conditions for 2.5 seconds, the trial terminated.

Figure 1. Experimental configuration.

To initiate the unusual attitude (UA), straight and level flight was interrupted as the HUD screen was blanked for a period of 2 seconds. This interval of time was meant to simulate a time in which: (a) a simulated autopilot flew an emergency missile evasion profile and (b) the pilots eyes were diverted from the instrument panel. At the end of this interval the HUD screen was restored, and the pilot attempted to recover, first returning roll to an upright attitude, and then returning pitch to a level attitude. Only pitch downward UAs were imposed. On the rare occasions when radar altimeter reached zero (i.e., the plane crashed), the trial terminated. We accepted this risk because we wanted the UAs to be challenging, thus further inspiring the pilots to recover as quickly as possible.

Simultaneously with HUD restoration, three sorts of command inputs could be delivered:

(1) As shown in Figure 2, a quadrahedral icon would appear on the HUD display (Wickens et al, in press) with extensions that pointed in the direction of the required stick movement (i.e., left → roll left; up → pull up).

(2) A voice command would utter two phrases, a roll correction ("roll left" or "roll right") and a pitch correction ("pull up"). The roll command was repeated with 1.11 seconds between the commands until an upright attitude (< 90 degrees roll) had been restored, and then the pitch command was alternated with a roll command at the same rate.

(3) A tactile command. This was created by sweeping a set of 7 tactors across the torso, left→ right or right→ left, mimicking roll right and roll left commands, respectively. The duration of the sweep was 0.78 seconds. As with the voice commands, following restoration of an upright roll (< 90 degrees), the pitch-up commands were presented by sweeping a set of 5 tactors up the center of the torso, with a duration of 0.56 seconds. Tactile stimuli began with a stimulus on the side opposite the direction of desired response,

and intensified by means of more tactile activation as the sweeping motion reached the desired direction of response. The icon was always present redundantly whenever the voice or tactile commands were used; and the latter two commands initiated simultaneously with the appearance of the icon, which was at UA initiation. The timing of the tactile and voice commands was identical.

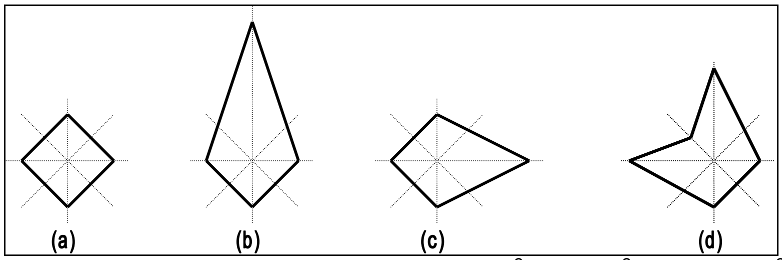

Figure 2. SD icon snapshots for an aircraft whose state is: (a) 0^{o} Pitch, 0^{o} Roll; (b) -90^{o} (down) Pitch, 0^{o} Roll; (c) 0^{o} Pitch, -45^{o} (left) Roll; and, (d) -45^{o} Pitch, +45^{o} Roll. The icon in the figure points in the direction(s) to correct for these states back to straight and level flight.

Each trial was flown until a criterion of straight and level flight, as described above, and then the trial terminated. The pilot was given approximately 1 minute before commencing the next trial.

Design

An entirely within subjects design was used, varying three factors orthogonally in a 4x2x2 design:

1. Four levels of display type were blocked within different trial sets (control, icon only, tactile with icon, voice with icon).
2. A random set of pitch and inverted roll deviations were assigned to two fundamental categories: severe inversion (at about 15 degrees from a complete 180-degree roll inversion) and moderate inversion (at about 60 degrees from complete inversion).
3. Each display condition, and its set of attitudes was encountered in two blocks, providing a replication (or learning) variable of two levels.

Within each replication x display block, four unusual attitudes were imposed. These included between 1 and 3 cases of severe inversions (and correspondingly between 3 and 1 cases of moderate inversion. Typically, there were 2 of each, but randomization sometimes yielded a 3-1 mix, never a 4-0 mix. Each of these four was also randomly assigned to 4 different levels of nose-down pitch: 30, 45, 60, and 75 degrees.

Practice trials always contained: [pitch 30, roll 110], [pitch 30, roll 260], [pitch 85, roll 140], and [pitch 85, roll 200]. (Where the roll convention used by Microsoft FlightSim is: upright level is 0; 90 degrees right roll is 90; inverted is 180; left 90 is 270; and, left 1 degree is 359. FlightSim also uses a pitch convention of positive as nose down.)

Each unusual attitude was encountered at a random duration between 10 and 30 seconds after the flight leg initiated. Each pitch and roll angle for the UA was further randomized by adding or subtracting up to 5 degrees so that pilots could not develop expectations for an upcoming UA's specific angles. For the first replication, the four display conditions were presented in a counter-balanced order across all pilots. Then each pilot encountered the second four replications in pseudo-random Latin square design (Table 1). The experimental protocol was approved by the local (Air Force Academy) IRB.

Table 1. Counterbalancing order.

Pilot	Condition (No Aid, Icon only, Audio, Tactile)							
1	T	A	I	N	N	I	A	T
2	N	I	A	T	T	A	I	N
3	A	N	T	I	I	T	N	A
4	I	T	N	A	T	A	I	N
5	N	I	A	T	A	N	T	I
6	A	N	T	I	N	I	A	T
7	T	A	I	N	A	N	T	I
8	A	N	T	I	T	A	I	N
9	T	A	I	N	I	T	N	A
10	N	I	A	T	I	T	N	A
11	I	T	N	A	A	N	T	I
12	I	T	N	A	N	I	A	T

Procedure

Upon arriving at the experimental facility, pilots read and signed the consent form, and then were introduced to the general procedures of the experiment. Each pilot was given 10 minutes (or as long as they felt appropriate) to familiarize himself with the flight dynamics, and then practice UA recovery in the control condition for 4 trials, or as long as he felt appropriate. Then, prior to each block of the first replication, pilots were given four trials or more (greater than four trials only happening in one case) to practice recoveries with a particular display type.

During the second replication, pilots were alerted to which display type they would receive prior to each block, but were given no further practice trials. Following the experiment, pilots were asked to complete a brief form requesting subjective ratings of each display, and inviting other comments. The entire experiment required approximately 90 minutes to complete.

Data Analysis

Data were analyzed in terms of a series of mission completion and flight safety measures, including the time to restore stable parameters (see above), minimum radar altitude flown, maximum g force, minimum time-to-impact the terrain, and maximum negative vertical velocity. In addition, the continuous measures of roll and pitch were evaluated during the first 10 seconds following the display re-appearance of each UA event, and visual analysis was used to determine the time and correctness of initiation of a roll correction, and of the subsequent pitch correction. Across all of these eight dependent measures, data were pooled across the different pitch upsets, as well as the 1-3 instances of severe or moderate inversion within each replication. All data were examined for normality, transformed if a high skew value required it, and subjected to SPSS repeated measures ANOVAs. Where necessary, subsequent planned contrasts examined directional hypotheses that all display augmentations would be superior to the control condition, and that the two non-visual augmentations would be superior to the icon alone.

Results

The initial roll response time data are shown in Figure 3, as a function of display condition and roll inversion severity. Analysis of these data revealed a significant main effect of display ($F_{3,33} = 9.00$, $p < 0.01$), a marginally significant effect of severity ($F_{1,11} = 3.51$, $p = 0.09$) and a significant display X severity interaction ($F_{3,33} = 3.58$, $p = 0.02$). Planned comparisons revealed that initial response times (RTs) were longer in the control condition than in the three display augmentation conditions, but that the latter three did not differ from each other. There was also a main effect of training replication ($F_{1,11} = 5.55$, $p < 0.05$), indicating a small (less than 0.1 second) reduction in RT from the first to the second replication.

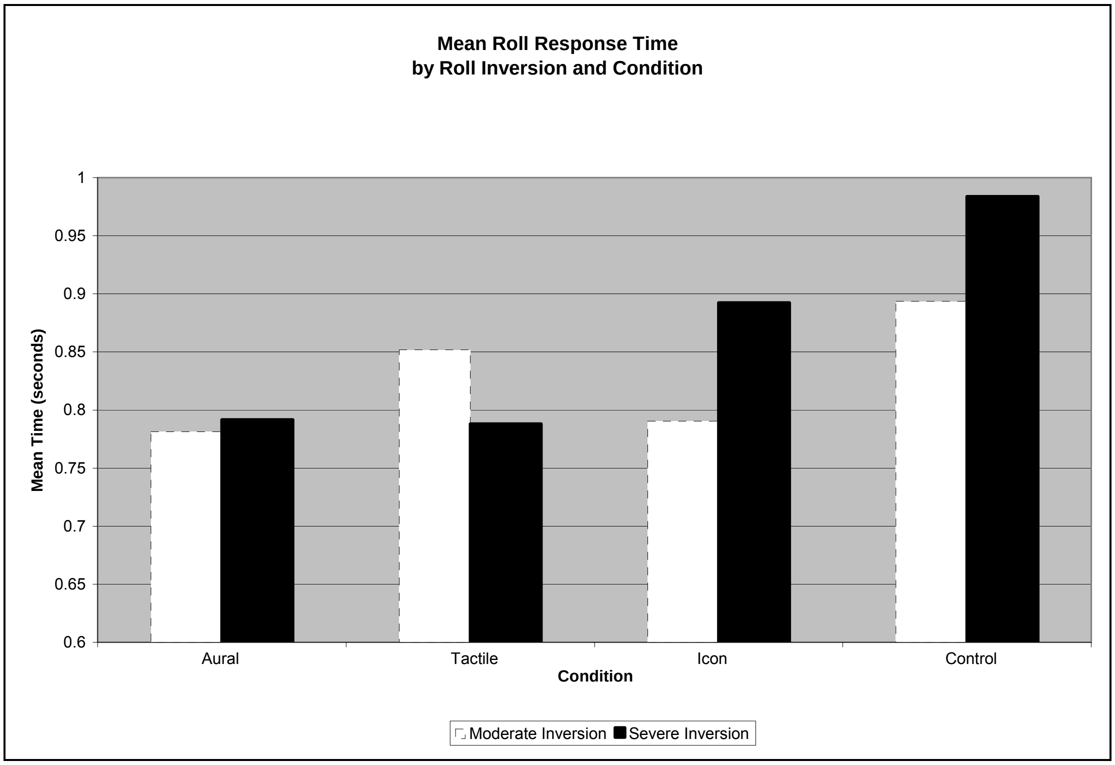

Figure 3. Initial response time as a function of display condition and severity of roll inversion (white: modest, black: severe).

In order to examine the significant interaction in more detail, the data in the "severe" inversion condition (at about 15 degrees from inverted) were submitted to a two-way 2 (replication) x 4 (condition) ANOVA. As would be expected, this ANOVA again revealed a significant effect of display ($F_{3,33} = 9.30$, $p < 0.01$). However in contrast to the ANOVA performed on the full data set (i.e., including the moderate inversion), this ANOVA revealed a clear advantage of the voice and tactile conditions over the icon-only condition. A planned contrast of the two former versus the latter yielded a significant benefit of the non-visual augmentation ($p = 0.04$), as seen in the black bars of Figure 3. This benefit was not present with the moderate inversion (i.e., at about 60 degrees from inverted).

In addition to initial roll response time, we also examined the frequency of roll reversal errors, characterized by an initial roll rotation in the opposite direction to that which was commanded (or was appropriate, in the case of the control condition). Such errors were committed on only a small proportion of the trials (14/384), and were distributed as follows: Voice 2, Tactile 4, Icon-only 1, and Control 8. A chi-squared test revealed that this distribution significantly ($p = 0.05$) departed from the hypothesis of equal proportions. Thus, as with initial response time, so accuracy appeared to benefit by the presence of a command display.

Pitch response time data were about 2 seconds longer and less consistent than the roll response, reflecting the fact that pilots appropriately rolled to an upright attitude before initiating their pitch recovery. Perhaps in part because of these factors, initial response time for pitch failed to reflect significant effects of any of the independent variables, nor their interactions.

The measure of overall time to restore straight and level flight also failed to reflect significant effects, as these times were quite long (averaging around 40 seconds), and clearly reflected the contribution of numerous factors in addition to the specific variables manipulated in the experiment.

Of the four measures of safety, two reflected a significant ($p < 0.05$) effect. First, the minimum radar altitude indicated that pilots descended 420 feet lower when recovering from a severe rather than a moderate roll inversion ($F_{1,11}=14.13$, $p < 0.01$). Further, an interaction between training replication and display condition ($F_{3,33} = 2.85$, $p = 0.05$) indicated that, earlier in practice (replication 1), the tactile and icon display allowed maintenance of a higher minimum altitude than the control and auditory displays; but in later trials (replication 2) all three augmentations produced lower descents than did the control condition. Second, the minimum time-to-impact measure revealed a lower time with severe (5.8 sec) than moderate (6.7 sec) inversions ($F_{1,11} = 5.46$. $p < 0.05$). While there was no effect of display condition ($F < 1$), an interaction between condition and practice ($F_{3,33} = 2.92$; Huynh-Feldt correction for sphericity, $p < 0.05$) revealed that early in practice, the tactile and control condition led to a greater time; whereas later in practice, the pattern reversed, with the voice and icon leading to a greater minimum time-to-impact. Finally, with regard to the ultimate measure of safety, it is noteworthy that the crash rate (minimum radar altitude = 0) was quite low, with only 9 crashes out of 384 opportunities. These crashes were relatively evenly distributed across the four conditions (2,2,2,3).

Finally, subjective ratings of display preference were analyzed. A t-test revealed that the overall evaluation of the tactile display was significantly lower than the icon display ($t_{22} = 2.20$, $p < 0.05$) and lower than the voice display ($t_{19} = 2.88$, $p < 0.05$). Of those who favored one display over another, eight pilots rated the voice display as most preferred; two rated the icon display as most preferred, while none rated the tactile display as most preferred.

Discussion

The current study set out to evaluate the effectiveness of attitude command displays, with and without redundant non-visual augmentations, to facilitate recovery from unusual attitudes for experienced Air Force fighter pilots. The results indicated that, while such displays were effective, their effectiveness was confined to the initial roll response to an inverted attitude. Here the results indicated that all three command displays were helpful in terms of both time and accuracy; and furthermore those with redundant non-visual augmentations (tactile and voice commands) were particularly helpful in initiating the response when the inverted attitude was severe (nearing 180 degrees). In this regard, the data are consistent with the findings of Calhoun et al. (2003) that a pure alerting (i.e., non-directional) system benefited from redundant aural or tactile display, as well as those of Van Erp et al. (2006) who found in a spatial disorientation context, that a directional tactile alert improved performance over a control condition. Our study combined these results by identifying the equal support of both tactile and voice-based directional commands, in a fairly realistic flight scenario, with skilled fighter pilots.

In interpreting these results, it is important to note that the two sensory augmentations offered neither earlier nor additional information to the command icon, but **did** provide a performance advantage, suggesting that the greater salience of these two modalities was somewhat more effective in capturing attention, relative to a visual-only cue. It is also important to note that the tactile cueing was everywhere just as effective as the voice display, in spite of the fact that voice commands are far more familiar than the tactile commands. In this regard, the data speak to the potential value of the tactile system. Finally, we note that the tactile cue was the least favored in terms of subjective ratings, and three of the pilots had strong negative comments to offer regarding its potential value. The observation that display augmentations which improve performance are not always preferred is one that has often been observed in human factors (Andre and Wickens, 1995).

While the initial response speed and accuracy benefited from command displays, we might also have expected that some of the benefits of augmentation (and particular non-visual augmentation) would have been reflected in other variables of greater duration (e.g., eventual time to full recovery, safety measures). The fact that they did not consistently do so (minimum altitude, time-to-impact), or do so at all, indicates that the relatively small gains in response time (tenths of a second), were masked by the considerable variability imposed by other factors in this time following initiation of the first roll.

In spite of this elimination of command display benefits for the longer duration measures, one can envision many circumstances in which slight gains in response time (and, in particular, elimination of initial roll reversal errors) could impose substantial safety benefits. Furthermore, it can be asserted that in some respects the current simulation was designed to make recovery relatively easy, compared to operational circumstances. For example pilots expected an inverted UA on every trial, and, for experimental reasons, this always produced a pitch-down attitude. Also, pilots were only engaged in a single task (notice and recover from UA), whereas in actual combat, there could have been several concurrent tasks competing for their attention; for example, visual scanning for a target, auditory communications with a wingman, auditory processing of in-cockpit warnings. In particular, the latter two auditory inputs might have placed the current voice cuing at a disadvantage, compared to the tactile cueing. In short, we would predict that if either or both of these factors (expectancy, concurrent task load) were altered to more closely mimic real world combat situations, the advantages of command displays, of non-visual command displays, and particularly of tactile command displays, would be elevated considerably.

Conclusion

In conclusion, the current results strongly point to the advantage of command displays to facilitate recovery from unusual attitudes, and suggest that research on voice and tactile displays be pursued under conditions when multi-task workload and low expectancies are created, as well as those in a motion based simulator, imposing vestibular disorientation and high g-load (Erickson et al, 2006). Here we might expect these advantages will amplify.

Acknowledgments

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References

Air Force (Nov, 2001). *Flying Safety*. Washington, DC: author.

Andre, A.D., & Wickens, C.D. (1992). Compatibility and consistency in display-control systems: Implications for aircraft decision aid design. *Human Factors, 34*(6), 639-653.

Andre, A.D., & Wickens, C.D. (Oct 1995). When users want what's not best for them: A review of performance-preference dissociations. *Ergonomics in Design*, 10-13.

Begault, D.R., & Wenszel, E.M. (1992). Techniques and applications for binaural sound manipulation in human-machine interfaces. *International Journal of Aviation Psychology. 2* (1), 23-38.

Braithwaite, M., Ercoline, W.R., & Brown, L. (2004). Spatial disorientation instruction. In F.H. Previc & W.R. Ercoline (Eds.), *Spatial disorientation in aviation.* Reston, VA: AIAA, 323-378.

Brickman, B.J., Hettinger, L.J., & Haas, M.W. (2000). Multisensory interface design for complex task domains. *International Journal of Aviation Psychology, 10* (3), 273-290.

Erickson, L., van Erp, J., et al. (2006). Vibrotactile and visual threat cuing with high G threat intercept in dynamic flight simulation. *Proceedings 50th Conference of Human Factors and Ergonomics Society.* Santa Monica, CA: HFES.

Ho, C.Y., & Sarter, N.B. (2004). Supporting synchronous distributed communications and coordination through multimodal information exchange. In *Proceedings of the 48th Annual Meeting of the Human Factors and Ergonomics Society*. Santa Monica, CA: HFES.

Holmes, S.R., Bunting, A., Brown, D.L., Hiatt, K.L., Braithwaite, M.G., & Harrigan, M.J. (2003). Survey of spatial disorientation in military pilots and navigators. *Aviation, Space, and Environmental Medicine, 74*(9), 957-965.

Kovalenko, P.A. (1991). Psychological aspects of pilot spatial orientation. *ICAO Journal, 46*(3), 18-23.

McGuirl, J. and Sarter, N.B. (2001). Presenting in-flight icing information: A comparison of visual and tactile cues. In *Proceedings of the 20th Digital Avionics Systems Conference*. Reston, VA: AIAA.

Newman, R.L., & Haworth, L.A. (2004). Flight displays II: Head-up and helmet-mounted displays. In F.H. Previc & W.R. Ercoline (Eds.), *Spatial disorientation in aviation.* Reston, VA: AIAA, 451-507.

Previc, F.H., & Ercoline, W.R. (1999). The “outside-in” attitude indicator revisited. *International Journal of Aviation Psychology, 9*(4), 377-401.

Reising, J., Liggett, K.K., & Munns, R.C. (1999). Controls Displays and workplace design. In D.J. Garland, J.A. Wise, and V.D. Hopkin (Eds.), *Handbook of Aviation Human Factors*. Mahwah NJ: Erlbaum.

Sarter, N. (in press). Multiple resource theory as a basis of multimodal interface design. In A. Kramer, A. Kirlik, and D. Wiegmann (Eds.), *Attention: From theory to practice*. NY: Oxford U Press.

Sarter, N. & Schroeder, B. (2001). Supporting decision making and action selection under time pressure and uncertainty: The case of in-flight icing. *Human Factors, 43*(4), 573-583.

Sklar, A.F., & Sarter, N.B (1999). Good vibrations: The use of tactile feedback to support mode awareness on advanced technology aircraft. *Human Factors, 41* (4) 543-552.

Sundstrom, J. N. (2004). *Flight Conditions Leading to Class A Spatial Disorientation Mishaps in U.S. Air Force Fighter Operations: FY93-02* (Masters of Public Health Thesis). Washington, D.C.: The Department of Preventive Medicine and Biometrics of the Uniformed Services University of the Health Sciences.

Van Erp, J., Groen, E., Bos, J. & Van Veen, H (2006). A tactile cockpit instrument supports the control of self-motion during spatial disorientation. *Human Factors, 48 (2)* 219-228.

Van Erp, J, Veltman, J.A., & van Vern, H.A. (2003). A tactile cockpit instrument to support altitude control. In *Proceedings Human Factors and Ergonomics Society 47th Annual Meeting*. Santa Monica, CA: HFES.

Wickens, C.D., & Hollands, J. (2000). *Engineering psychology and human performance* (3rd ed.). Upper Saddle River, NJ: Prentice Hall.

Wickens, C.D. (2003). Aviation displays. In P. Tsang & M. Vidulich (Eds.), *Principles and Practices of Aviation Psychology* (Chapter 5, 147-200). Mahwah NJ: Erlbaum.

Wiegmann, D., Faaborg, T., Boquet, A., Detwiler, C., Holcomb, K., and Shappell, S. (2005). Human Error and General Aviation Accidents: A comprehensive fine-grained analysis using HFACS. DOT/FAA/AM technical report AM-05/24. Washington DC: Federal Aviation Administration.

ISAP 07 SDO submission (Wickens)
Vestibular-based spatial disorientation (SD) represents a recurring and potentially fatal problem in all aspects of aviation. For example, the US Air Force's costs associated with SD have averaged over $40 million per year over a recent 10-year period (Sundstrom, 2004). The Army, Navy, and civilian aviation experience similar SD costs (Sundstrom, 2004). While the problem is not as extensive in airline operations, this domain is also not without examples of severe disorientation (e.g., recent Dubai crash), and the consequences of such accidents are tragically high.

In our proposed presentation, we overview the collective results of a 3-year effort, carried out for the Air Force (*Multisensory Integration for Pilot Spatial Orientation*, AFRL contracts F33615-03-M-6360 and FA8650-04-C-6457), to study spatial disorientation, with particular focus on fighter pilots, but generalizing to broader aviation domains. Our paper will focus on four areas: developing a computational model of vestibular orientation, validating this model through empirical research, deploying the model in an on-line tool to prevent vestibular disorientation, and deploying it in an analytical tool for mishap investigation.

The Vestibular Model. Following the classic work of Gillingham and others (1993), we have integrated the existing literature on the response of both the semi-circular canals, and the otolith organs, to develop a computational model of how aircraft motions yield vestibular-based sensations of aircraft attitude that are discrepant from the actual attitude (Small et al, 2005). Particular emphasis has been placed on modeling 4 illusions: the leans, the graveyard spiral, the somatogravic illusion, and the Coriolis illusion.

Experimental Validation. An experiment to validate a critical component underlying both the leans and somatogravic illusion model was conducted within a motion-based simulator, in which the vestibular washout and the illusory counter-rotation of the semi-circular canals were examined. Experimental results comparing actual motions to the perceived motions provided data for fine tuning the model parameters.

SOAS Intervention Tool. A validated model could be implemented in the cockpit, receiving inputs from aircraft attitude and some aspects of pilot control behavior to infer the degree of spatial disorientation (discrepancy between perceived and actual attitude). Depending on the degree of inferred disorientation, graded interventions would be adaptively implemented to restore orientation. In one experiment (Wickens et al., in press), we examined the viability of less intrusive HUD located visual icons for such restoration. In a second experiment we evaluated the viability of more intrusive voice and tactile interventions that are designed to be triggered if the icons fail.

SDAT Analysis Tool. Continuous flight data available post-mishap from HUD tapes, aircraft data recorders, and ATC radar data have been input to a Spatial Disorientation Analysis Tool (SDAT) that we developed to reveal the likelihood that pilots experienced different states of disorientation, during the progression of the mishap flight. This tool has been successfully applied to characterize the spatial disorientation of specific mishaps such as Air Force F-16s, a Navy transport, and several general aviation accidents.

Appendix B. Results of SDAT Heuristic Evaluation

A Heuristic Evaluation of the SDAT user interface was performed to evaluate its usability. Three usability experts were consulted. Their qualifications are listed below, and the results of their evaluations follow.

Evaluator Qualifications

John Milanski is a Staff Human Factors Engineer with eleven years of experience conducting usability, human factors, and programming projects using methods such as heuristic evaluation, usability testing, rapid ethnography, and rapid prototyping. Mr. Milanski has a B.S. in Aerospace Engineering and Masters in Human-Centered Product Design with a focus on field research.

As a cultural anthropologist at Alion, Ursula Lauper is responsible for conducting user-centered research and usability analyses for product development. Recently, she has performed field research and product evaluations for DARPA and the U.S. Army Research Lab. Ms. Lauper has a Masters in Cultural Anthropology.

Dr. Lila Laux is a Senior Cognitive Engineer at Alion with over 25 years of experience in the fields of human factors and psychology. In addition to eight years as a professor, Dr. Laux has focused on developing and practicing methods to assess individual skills and predict performance. Dr. Laux has degrees in Biology, Applied Psychology, and Human Factors.

Results of Heuristic Interface Evaluation

Heuristics Violated Index

1 = Match system-real world (familiar words, intuitive layout)
2 = Consistent interface/follows interface standards (words, objects, operations, behaviors)
3 = Visible system status (provides constant feedback)
4 = Error preventions
5 = Error recovery (clear messages)
6 = User Control (provides exits/undos)
7 = Visual clues for user action
8 = Aesthetics/minimalistic design (relevant info, aligned, consistent placement)
9 = Recognition over using memory (don't have to remember info)
10 = Makes the user smart (reduce the need for memory, calculating relation)
11 = Flexibility/efficiency of use (novice/expert use, tailoring)
12 = Help/documentation (task focused, not too large, easy to search)

Severity Rating Index

1 = Frequency (H, M., L)
2 = Impact (H, M, L)
3 = Persistence/Difficulty to work-around (H, M., L)
4 = Overall Severity: 1=Severe, 2=Major, 3=Minor, 4=Cosmetic

Issue	Screen	Evaluator	Issue	Significance	Heuristics Violated	Severity Rating 1	2	3	4	Suggestion
24	2D-Altitude Indicator	Milanski	BUG: Not sure the displayed values are correct			h	h	h	1	
52	2D – Data to plot selection bar	Lauper	Selected boxes don't refresh to default when a new scenario is run	If user selects an assortment of graph types to view (whether or not Reset is selected), the boxes stay checked if a new scenario is started. Is this the behavior that users would expect?		l	l	m	4	
46	2D – Event Sequence 1-4 y-axis on illusion Flags tab	Lauper	How is Event defined? An SDAT event is a "step" in a disorientation illusion. For example, the 1st Leans event is a sub-threshold roll of a certain amount for a certain duration	What's the difference between the 4 events? Why will things show up at different (discontinuous) times under the same event		h	m	m	2	

Issue	Screen	Evaluator	Issue	Significance	Heuristics Violated	Severity Rating 1	2	3	4	Suggestion
65	2D – illusion flags tab	Milanski	A grid would make it easier to interpret results			l	m	l	4	
66	2D – illusion flags tab	Milanski	Illusion Event graph should have the same length x-axis as the Results Graphs, rather than stopping after the last observed illusion event			m	m	l	3	
70	2D-illusion flags tab	Milanski	Unclear what 'event' means in this context – is a timeline created for every SD event?			m	l	l	3	
56	2D – illusion flags tab	Lauper	Coriolis scenario doesn't trigger an illusion event	Is it only picking up Leans for now?		m	h	h	2	
69	2D – illusion flags tab	Milanski	Illusion Flags are not being generated when illusion Type is set to 'All'			m	h	h	2	
27	2D – Results Graph	Milanski	Would be helpful to see a history of the countermeasures employed and their type			l	l	l	4	
53	2D – Results Graph	Lauper	If all graph options have been deselected, the original set will continue to run while the selection boxes remain empty	Should the check boxes automatically repopulate to reflect the current graphs if a selection error (e.g., deselection all graphs) is made?		l	m	l	4	
73	2D – Results Graph	Milanski	A grid would make it easier to interpret plots			l	m	l	4	
74	2D – Results Graph	Milanski	Hidden Feature: Had no idea you could pause the cursor over a point on the graph and the x-y value would appear in a tooltip			l	l	l	4	
13	2D – Results Graph	Milanski	Don't know you can select 4 data series until you high the REFRESH button			h	l	l	3	Change label ('Select up to 4')
14	2D – Results Graph	Milanski Laux	Extra clicks: Why must the user hit the REFRESH button?	Clicks are precious. Removing clicks makes the UI easier and faster to use. Isn't this really a button that means 'Display' currently selected graphs? (Lila)		m	l	l	3	
15	2D – Results Graph	Milanski	to 4 data series? What if the user has a large display?			m	l	l	3	
29	2D – Results Graph	Milanski	on that you must select one data series			h	l	l	3	
30	2D – Results Graph	Milanski Laux	Long list of data series is difficult to search. They should be grouped categorically (Lila)			h	l	l	3	

Issue	Screen	Evaluator	Issue	Significance	Heuristics Violated	Severity Rating 1	2	3	4	Suggestion
31	2D – Results Graph	Milanski	No data labels for y-axis			h	l	m	3	
51	2D - Results Graph	Lauper	No way for users to know they can only select a minimum of 1/maximum of 4 graphs	Provide some indicator that 1-4 must be selected. E.g., a text message and/or deactivating check boxes after 4 have been selected, or preventing deactivation if the last one is deselected		m	l	l	3	
16	2D – Results Graph	Milanski	The dynamic y-axis on the time plots can make insignificant changes appear dramatic, i.e., misrepresents data.			h	m	m	2	
32	2D – Results Graph	Milanski	The dynamic x-axis on the time plots can make insignificant changes appear dramatic, i.e., misrepresents data			h	m	m	2	
98	2D – Results Graph	Laux	Scale used for the actual vs. perceived in some instances. This makes comparison difficult.	when the scale for roll is -80 to 80 and the scale for perceived roll is -150 to 150, the graphs don't look very different, but in fact there is a huge difference		h	m	m	2	
99	2D – Results Graph	Laux	The actual and perceived graphs for each type should be presented one above the other graphs			h	m	m	2	
54	2D – Results Graph	Lauper	Plots do not clear after Halt and New are selected	All other tabs clear their data except this one		m	m	h	2	
40	All – 'Auto-Hide' display option	Lauper	Full 'down carat' display options are not available if the window is in the Auto-Hide mode	Floating and Tabbed Document don't become available until Dockable is selected		m	m	m	2	
44	All – 'Step' simulation icon label	Lauper	odd label – step is correct because they want the sim to go one "step" at a time.	At first glance I thought it was a typo for "Stop". Maybe "Advance"?		l	l	l	4	Saint Issue
48	All – Abort Simulation	Lauper Laux	No icon for this function on control bar. Also, no description in the manual (Laux)	Unlike the other control bar features (play, step, halt, etc.) the only way to access Abort is via Execution on the menu bar		l	m	m	3	
43	All – Blue hot link text	Lauper	Inconsistent functionality	Clicking Select Flight Data File acts as a check to make sure the file is valid; clicking some other labels brings up the contextual user guide; clicking till others does nothing. I'm assuming most text will eventually be linked to the user manual, but that till means that Select Flight Data File acts differently from the others		m	l	l	3	
45	All – Halt and Abort Simulation Labels	Lauper	unclear of the difference between them? Abort cancels the sim and collects no data. Halt stops the sim but can			m	m	h	2	SAINT ISSUE

Issue	Screen	Evaluator	Issue	Significance	Heuristics Violated	Severity Rating 1	2	3	4	Suggestion
			begin the sim where it left off.							
50	All – Halt to Step simulation	Lauper Laux	Changing from Halt to Step mode clears out the Results Graph tab	Since the simulation isn't starting over from the beginning I would expect the Results Graph to continue where they left off. I agree (Lila)		m	m	m	2	
75	All – Input	Laux	Cannot use the Enter key on all windows where there is an OK button – this is non-standard	aggravating	2, 6, 11	m	l	l	3	
18	All –Main	Milanski	BUG: The app seems to crash when a data set is fun in full screen mode			m	h	m	2	
5	All – Main Screen	Milanski Laux	Inconsistent: Default order of the tabs (Analysis-Illusion-Results-Animator-Counter) does not match the order in the View-Windows drop menu (Alphabetical)	The order should convey some information, e.g., order of steps, importance, rather than just being random. I don't think the order is "random" I think they are in the order that you have asked to "View" them from the View Menu – I noticed the order changed every time I hid them and then reinstantiated them from the View menu. This creates inconsistency, but I don't know what to do about it… (Lila)	4, 7, 8, 9, 10	l	l	l	4	
12	All – Main Screen	Milanski	Non-Standard: Can't access HELP using the menus, only through hyperlinks		2, 12	m	l	l	3	Allow Help to be accessed from Help menu
67	All – Main Screen	Milanski	The tabs are not equivalent but they are presented that way, i.e., one is setup, the others are results			h	l	l	3	Separate the setup tab from results tab with a space or blank tab?
1	All – Main Screen	Milanski	BUG: When trying to expand the screen using the upper right corner, an error was generated ("Unhandled exception has occurred in a component in your application…")		5	h	h	m	1	
97	All – Main Screen – Textboxes on Analysis Setup	Laux	The red circle with an exclamation point that instantiates upon unacceptable entry into the text field is non-standard and there is no explanation of what it is or that the reason the app doesn't run is because you have an error here. It seems like it the user is being warned rather than given an error message (warning means that there is a serious hazard). The roll over explanation is good, but the user has to see the symbol and roll over it. There is no explanation of the icon in the User's Guide	When the app doesn't run after the "Begin Simulation " icon is pressed, the user may not know why and may not "get" the red circle icon	2, 5, 7, 9, 10, 12	l	l	m	3	Explain the icon in the manual at the point where it could appear.
6	All – Main Screen View	Milanski	Unnecessary complexity: View-Layout drop menu has only one option and it is related to View-Windows			h	l	m	3	View-Windows and View-Layout could be combined into one list under

Issue	Screen	Evaluator	Issue	Significance	Heuristics Violated	Severity Rating 1	2	3	4	Suggestion
										View
25	All – Main – Simulation Speed	Milanski	Drop list next to speed icon does not indicate the current simulation speed		3	h	l	h	3	SAINT ISSUE
59	All – Menu – Open function	Lauper	File-Open only looks for saint files, whereas 'select flight data file' wants a .xls file	Will the user understand that 'open' and 'select file' are looking for different things		m	h	m	2	
60	All – Menu bar	Milanski	Why isn't there an Autosave setting			l	h	l	3	
61	All – Menu bar	Milanski	Field validation should remove the need to "Check for errors"?			h	l	l	3	
62	All – Menu Bar – Execution – Play	Milanski	Why does Pause-Play erase data points prior to the pause but Pause – Resume does not?			m	h	h	2	
2	All – Menu Bar – View – Windows	Milanski	Inconsistent with Animator 3D icons. Expected that icons to left of listed windows would indicate that the window was opened or closed, like the icons do for Animator 3D – Show Floor Grid (which provides good user feedback)		2, 7	h	l	l	3	
47	All – Pause vs. (re)play function	Lauper	Pressing Play after Pausing deletes previous lines in Results Graph (toggling Pause on and off works fine)	Is there any way to keep restart from where it left off? I noticed in the user guide that this is intentional but I don't understand why. Will the users? I agree (Lila)		h	h	h	1	SAINT ISSUE
38	All – Sections sliding window	Lauper Laux	Unnecessarily redundant. What utility does this have?	Users can already select screen sections via the tabs on the main window or through View on the menu bar. Why do they need a 3rd method, especially since it's located right next to the tabs?		m	l	l	3	
39	All – Sections sliding window	Lauper	Order of sections doesn't match tabs	Tabs list the sections in a different order from the Sections slider		m	l	m	3	
49	All – Simulation feature	Lauper	Double-click is needed for function to work	Seems to be working as an on/off toggle, which doesn't match the functionality. If the purpose of the feature is to advance the simulation by x%, then each click should do just that. Having an "off" mode for something that doesn't continue on its own doesn't make any sense		m	m	m	2	SAINT ISSUE
58	All – Simulation speed indication	Lauper	There's no indication on the interface that tells the user what speed the simulation will run/is running at	I see it hasn't been set up in Execution settings yet. Depending on how users play with this, they might		l	l	l	4	SAINT ISSUE

Issue	Screen	Evaluator	Issue	Significance	Heuristics Violated	Severity Rating 1	2	3	4	Suggestion
				want a "speed" display that's continually visible when they're running simulations						
57	All – Simulation Speed Selection	Lauper	The drop-down speed selection menu has no check mark, so the user gets no feedback to indicate which is currently selected, and if a new selection has registered	Check mark should appear next to the current speed		n	h	h	2	SAINT ISSUE
42	All – View Menu Bar	Lauper	No way to re-open individual dockable windows Sections, Output, and Attitude Indicator after they've been closed out except to reset the entire interface.	E.g., my first instinct is to click the X on the Sections slider to close it (instead of waiting for it to close). This removes the slider from the interface. The only way to get it back is to select View-Layout=Reset Screen Layout. What about making each of the dockable windows available for reopening individually through the same menu?		n	n	h	2	SAINT ISSUE
41	All – View – Windows menu bar	Lauper	Naming inconsistent with Sections slider	Are these "windows" or "sections"? If we're keeping both navigation methods the naming should be consistent		l	m	l	4	
93	All Windows	Laux	There is really only one window in this application by Windows standards – the Main Window (which is a frame with the panes in it). All of the other parts of the window should be referred to (especially in the manual) as panes (viewing areas within windows)		1, 2, 12	h	l	l	3	
68	Analysis setup	Milanski	Should sample rate be in terms of hz or sample/sec			l	l	l	4	
4	Analysis setup	Milanski	Non-standard use of dimming: Before an analysis is done, the Recovery – Coriolis – Graveyard – Leans tabs are grayed out, but still able to activate those tabs. Usually grayed –out indicated that the feature is unavailable/can't be selected. Also differs from the way the main tabs are displayed. (Analysis – illusion – Results…)		2, 7	h	l	l	3	
7	Analysis Setup	Milanski	Non-Standard Checkboxes: Until the SW allows for checking of multiple illusion Types. The selection should be radio buttons.		2	h	l	l	3	Radio buttons
8	Analysis Setup	Milanski Laux	Inconsistent hyperlinks: Some underlined words link to help, others do not	Too many proposed hyperlinks anyway – should only allow linking to "higher" levels, not to every field in a pane (Lila)	2	h	l	m	3	
9	Analysis Setup	Milanski	"2 decimal places" appears to indicate that this is the default, but it is not labeled as in other areas		2, 6	h	l	m	3	

Issue	Screen	Evaluator	Issue	Significance	Heuristics Violated	Severity Rating 1	2	3	4	Suggestion
11	Analysis Setup	Milanski	Non-Standard checkboxes: Washout function choices should be checkboxes if only one can be chosen	Actually, Washout function choices should be radio buttons if only one can be chosen (Lila)		h	l	l	3	
33	Analysis Setup	Milanski Laux	When model is running, all fields on this screen remain active	Implies it is possible to change settings and effect results while model is running		h	m	l	3	Should be grayed out when the model is running
34	Analysis Setup	Milanski	Program does not display the actual data sampling rate used (e.g., user specifies 8 Hz but the data file only goes down to 4Hz and that is what the program runs at)			m	m	l	3	Prescan the file when it is selected, and place a limit on data sampling rate equal to that in the file.
35	Analysis Setup	Milanski	Is it possible to use sliders for acceptable values in all setup fields along with the text entry box?			h	l	l	3	
94	Analysis Setup	Laux	Data rounding field – if enter a lot of numbers it presents the red error circle (see above), even when you have presented an integer that "fits" in the field. The roll over message says: "Not a valid entry must be set to an integer value" which does not tell you what the problem is. And the red circle doesn't go away when you replace whatever you have put in there with 2 (which is the default value) until you go to another field		1, 3, 4, 5, 7, 10, 12	m	m	l	3	
10	Analysis Setup	Milanski	Data Rounding label gives no clues of the values allowed		4	h	m	m	2	
95	Analysis Setup – Countermeasures	Laux	Misspelled demonstrate			l	l	l	4	
26	Analysis Setup – Countermeasures	Milanski	Doesn't show the possible values for each field			h	l	l	3	
28	Analysis Setup – Countermeasures	Milanski	No feedback about how the algorithm determines countermeasure		3	h	l	h	3	Provide a visual link between the cause (e.g., disorientation type) to the effect (countermeasure)
89	Analysis Setup – Create New Analysis	Laux	Data Sampling Rate – very opaque to the user. What are they able to select? What happens if they put in a value that is very unrealistic? It lets you enter ANY value						3	
96	Analysis Setup – Output	Laux	What is the unit for duration and why does it have 12 decimal places (if this is seconds, that is a VERY small amount of time)		2, 7				3	2 dec places max and unit (sec)
90	Analysis Setup – Reset to Defaults buttons	Laux	These buttons typically belong to panes in the Main window, but it is not necessarily clear which fields they relate to. Standard Windows design would put them						3	

Issue	Screen	Evaluator	Issue	Significance	Heuristics Violated	Severity Rating 1	2	3	4	Suggestion
			inside a Group box with all of the controls they relate to, but here the panes are not clearly delineated and the controls are not grouped.							
55	Analysis Setup – Select Illusion Type	Lauper Laux	Leans is the default instead of all	I'd expect All to be the default. I would not expect any default unless you have checked with users and determined from them which one they will use most of the time (Lila).		h	h	l	3	
36	Analysis Setup – Vestibular	Milanski Laux	The tab order seems random. The tab order on all of the tabs and windows seems random (Lila)						3	make the tab order logical or take out tab ability
77	Animato 3D Settings Tab	Laux	Should be disabled because it isn't functional						4	
20	Animator 3D	Milanski	Hidden feature: No indication that the viewpoint can be zoomed using the mouse scroll wheel			l	m	l	4	
22	Animator 3D	Milanski	What does the axes relate to? Mag north? Maybe should be relabeled 'pitch, roll, yaw" rather than "x,y,z"		1, 2	l	l	h	4	
72	Animator 3D	Milanski	Unclear what 'Exceeds Threshold"	refers to (pitch, roll, yaw)		l	l	l	4	
19	Animator 3D	Milanski	Possible to drag the axes/planes off screen where they are "lost"			l	m	h	3/4	
17	Animator 3D	Milanski	Hidden feature: No indication that the viewpoint can be changed by dragging the axes.			l	m	m	3	
23	Animator 3D	Milanski	What is the difference between the three 'velocity' labels		4, 9	h	l	l	3	Change label to 'pitch velocity' etc.
64	Animator 3D	Milanski	BUG: At the end of an 800% speed run, while on the Animator 3D screen, a message popped up saying "Animator 3D is currently in Execution mode. Do you want to switch to edit mode?"			l	m	m	3	
21	Animator 3D	Milanski	Hard to compare data: the main function seems to be to compare actual to perceived, but the data is separated on screen making comparison harder.			h	m	h	2	Place data in four columns: labels, actual, perceived, and plane view. "Plane view" means a top down view of the two aircraft icons overlaid or very close to each other.

Issue	Screen	Evaluator	Issue	Significance	Heuristics Violated	Severity Rating				Suggestion
						1	2	3	4	
63	User Guide	Milanski	User Guide says that the simulation speed cannot be changed during playback (pg 19), but it seems to work			1	1	1	4	
71	User Guide	Milanski	p.21, Ch4 section describing 'results graphs' is mistakenly labeled 'analysis window'			1	1	1	4	
76	User Guide	Laux	Typos: p.57, os should be is; p65 Base should be based; certainly frequently misspelled in manual						4	
78	User Guide	Laux	p30 discussion of Task description windows/document windows no correct for SDAT						4	Take this out
80	User Guide	Laux	p 45 refers to a red 'x' button that can be used to close the window – there is none						4	remove "red"
81	User Guide	Laux	p 47 – Where is the Utilities menu? Simulation speed is not under a Utilities menu						4	change manual
83	User Guide	Laux	p 55 There is no "load" button. The button says "Open". Load is preferable						4	
84	User Guide	Laux	p.55 refer the user to the sections that explain the different illusion types later in the manual						4	
88	User Guide	Laux	p 57 next to last line-simultaneously with what?						4	
91	User Guide	Laux	Footnotes reverences missing						4	
92	User Guide	Laux	p. 74 Event 4 Vertical Speed definition seems the same as the definition for Event 4 Roll Angle			1	1	1	4	
79	User Guide	Laux	Hide and Close window mean the same thing – should use one term unless they actually produce different results						3	
82	User Guide	Laux	p. 47 There is no Analysis Window (this is referred to multiple times in the manual)						3	correct this
85	User Guide	Laux	p. 56 out of sync with the pane which has 4 choices (it adds "All")						3	

Appendix C. Patent Application

UTILITY APPLICATION

BY

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FOR

UNITED STATES PATENT

ON

METHOD FOR SPATIAL DISORIENTATION IDENTIFICATION, COUNTERMEASURES, AND ANALYSIS

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Express Mail No.: **EV 498086185 US**

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METHOD FOR SPATIAL DISORIENTATION IDENTIFICATION, COUNTERMEASURES, AND ANALYSIS

RELATED APPLICATION

[0001] This application claims priority of U.S. Provisional Application Serial Number 60/678,919, filed on May 6, 2005.

GOVERNMENT RIGHTS

[0002] The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of Contract FA8640-04-C-6457, awarded by USAF/AFMC, Air Force Research Laboratory, 2310 Eighth Street, Building 167, Wright-Patterson AFB, Ohio 45433-7801.

FIELD OF THE INVENTION

[0003] The invention relates generally to the field of human spatial disorientation (SD). It addresses the problems of identifying, correcting, and analyzing SD episodes as experienced by human subjects in environments where spatial disorientation may occur, such as, for example, an aircraft pilot in an aircraft.

BACKGROUND

[0004] Spatial disorientation (SD) is the mistaken perception of a person's position, attitude and motion relative to the earth or significant objects visible to the person, such as, for example, mountains, trees, buildings or the like.

[0005] Spatial disorientation is a normal human response to accelerations in flight, and has been recognized since the early days of flight. The cost of SD to the U.S. military is over $300 million per year, with comparable costs to U.S. civil aviation. Without question, SD contributes more to the cause of aircraft accidents (civilian as well as military) than any other physiological problem in flight. Regardless of flight time experience, all aircrew members are subject to disorientation.

[0006] Despite significantly increased research over the past decade, the rate of accidents caused by SD has not decreased. With few exceptions, the most recent research emphases have been limited to understanding the physiology of SD. The new knowledge gained by such research has not been translated into tools (e.g., training, displays, automation) that help pilots avoid SD and minimize its effects if it does occur. Although a very common experience for pilots in aircraft, SD events and their associated problems may also be experienced by boat operators, divers, astronauts, firefighters and other persons in environments where visual cues may or may not agree with the perceived feelings of motion. Simply stated, if a person is in an environment with low visibility and impaired attitude awareness, there is an elevated chance they will experience an SD event.

[0007] There are three types of SD, Type 1 – unrecognized, Type 2 – recognized and Type 3 – incapacitating, each of which is most commonly referred to with respect to aircraft pilots. With Type 1, the pilot is not aware of critical control or flight parameters of the aircraft, and therefore may control the aircraft with erroneous assumptions. With Type 2, the pilot perceives a problem (resulting from SD) but fails to recognize it as SD. Typically the pilot will believe that the aircraft instruments are malfunctioning. With Type 3, the pilot experiences such an overwhelming sensation of movement that he or she can not reorient himself or herself by using visual cues or the aircraft instruments.

[0008] A human being's perception of motion is a result of the vestibular system, otherwise known as the inner ear. The vestibular system (organ of equilibrium), consists of two structures – 1) the semicircular canals, which detect changes in angular acceleration; and 2) the otolith organs (utricle and saccule), which detect changes in linear acceleration and gravity.

[0009] The semicircular canals are three half-circular, interconnected tubes in three planes perpendicular to each other. Each plane corresponds generally to rolling, pitching or yawing motions. Although there are two systems (one for each ear), they are collectively in operation as one system. Each canal is filled with a fluid called endolymph. A motion sensor is provided in the form of cupula (a gelatinous structure) and hairs extending from hair cells below the cupula; the ends of the hairs are embedded in the cupula. The cupula and the hairs move as the fluid inside the canal moves in response to an angular acceleration.

[0010] The otolith organs, the saccule and utricle, are located in each ear and are set at right angles to each other. The utricle detects changes in linear acceleration in the horizontal plane, while the saccule detects gravity changes in the vertical plane. Inertial forces resulting from linear accelerations cannot be distinguished from the force of gravity.

[0011] As the issue of SD can lead to loss of life and the destruction of property, several prior art methods have been developed in various efforts to address SD with respect to aircraft pilots. This art includes flight simulation devices such as described in U.S. Pat. No. 4,710,128 to Wachsmuth et al., which provides a controlled environment for creating SD events. However, certain SD events arise from conditions below human perception thresholds.

[0012] Also in the related art is U.S. Pat. No. 5,285,685 to Chelette, which provides a method and apparatus for communicating perceived attitude information from a test subject. Again, although perhaps beneficial for some instances of SD, there are forms of SD which are below perception and others that are so overwhelming that the subject loses all perception of perceived attitude.

[0013] U.S. Pat. No. 5,629,848 to Repperger et al., is focused upon an SD detector system capable of warning a pilot of potentially disorienting flight conditions in response to a Kalman filter modeling of human response characteristics. More specifically, a Kalman apparatus produces a state estimate of both the true position and orientation, as well as the pilot's perceived position and orientation of the aircraft.

[0014] The Repperger system is based in part on both the otolith and semicircular canal responses of human physiology. The Repperger system is an on-board only system, active only during flight, and its function is to determine only when an SD event is or is not occurring. When an error of sufficient magnitude occurs between the Kalman filter's true value and perceived estimate, an SD event is deemed to be occurring and a visual warning is provided to the pilot.

[0015] Repperger does not consider the developing probability of the SD event or the type of SD event. In addition, Repperger does not provide for post-event analysis and/or comparison to other similar events. Further still, Repperger does not consider either a range of warnings or different methods and/or types of delivery selected for the best chance of reaching the subject pilot and helping him or her overcome the SD event.

[0016] Hence, there is a need for a spatial disorientation identification method and system that overcomes one or more of the technical drawbacks identified above.

SUMMARY

[0017] The present disclosure advances the art by providing a system and method for spatial disorientation identification, countermeasures and analysis.

[0018] In particular, and by way of example only, according to an embodiment, provided is a computer-readable medium on which is stored a computer program for detecting, analyzing and responding to a spatial disorientation event. The computer program includes an input routine operatively associated with an input device for receiving real time data, recorded data, subject preference information or combinations thereof. The data include environment data from an environment, the environment data including true position and orientation of the environment, and subject data from a subject within the environment. A vestibular attitude calculator routine computes the perceived subject attitude of the subject within the environment based on the environment data and subject data. The vestibular attitude calculator includes a Washout routine to calculate a Washout value; a vestibular illusion routine to calculate the probability of a vestibular illusion; a threshold adjustment routine permitting adjustment of Washout thresholds and vestibular thresholds based on provided subject preference information; a countermeasure routine operating in response to the Washout value and the probability of a vestibular illusion, and an output routine operatively associated with an output device to provide the true position and orientation of the environment and the perceived subject attitude.

[0019] In an alternative embodiment, provided is a method for analyzing a spatial disorientation event post-hoc, including: collecting environment data elements recorded from an environment; collecting subject data recorded from a subject within the environment; calculating perceived subject attitude of the subject within the environment for each environment data element; evaluating the environment data, the subject data and the perceived subject attitude to determine the probability of a spatial disorientation event, and reporting the probability of the spatial disorientation event.

[0020] In yet another alternative embodiment, provided is a method for combating spatial disorientation, including: collecting real time environment data from an environment; collecting real time subject data from a subject within the environment; calculating perceived subject attitude of the subject within the environment for each environment data element and predicting Washout; evaluating the environment data, the subject data, the perceived subject attitude and Washout to determine the probability of a spatial disorientation event and the type of spatial disorientation event; implementing, in response to the probability of a spatial disorientation event, at least one countermeasure; and recording the environmental data and subject data as event data for post-hoc review. The environment data include true position and orientation of the environment; the Washout evaluated as a non-linear element, and the countermeasure is selectively chosen from a group of multi sensory countermeasures and countermeasure actions based on the environment data and spatial disorientation probability.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] FIG. 1 shows a high level block diagram for a spatial disorientation identification system in accordance with an embodiment;

[0022] FIG. 2 is a graph illustrating the non-linear property of Washout;

[0023] FIG. 3 is a graph illustrating the Leans illusion model according to an embodiment;

[0024] FIG. 4 is a graph illustrating the Coriolis illusion model according to an embodiment;

[0025] FIG. 5 is a graph illustrating the Graveyard Spiral illusion model according to an embodiment;

[0026] FIG. 6 is a high level flowchart illustrating spatial disorientation detection in real time with recordation for post hoc review according to an embodiment; and

[0027] FIG. 7 is a high level flowchart illustrating spatial disorientation detection in post hoc review.

DETAILED DESCRIPTION

[0028] Before proceeding with the detailed description, it is to be appreciated that the present teaching is by way of example, not by limitation. The concepts herein are not limited to use or application with a specific type of system or method for combating spatial disorientation. Thus, although the instrumentalities described herein are for the convenience of explanation shown and described with respect to exemplary embodiments, it will be appreciated that the principles herein may be equally applied in other types of methods and systems for detecting and combating spatial disorientation.

[0029] FIG. 1 is a high level block diagram of the computer program architecture of a spatial disorientation (SD) system **100** in accordance with at least one embodiment. SD system **100** may be implemented on a computer having typical computer components, such as a processor, memory, storage devices and input and output devices. During operation, SD system **100** may be maintained in active memory for enhanced speed and efficiency. In addition, in at least one embodiment, SD system **100** may be operated on a computer network and may utilize distributed resources.

[0030] To further assist in the following descriptions and discussion, the following defined terms are provided.

[0031] "Environment" – An aircraft, boat, vehicle or other setting which may provide conditions for an SD event to occur. In at least one embodiment, the Environment is an aircraft.

[0032] "Subject" – A person within the environment subject to the possibility of experiencing an SD event. In at least one embodiment, the Subject is an aircraft pilot.

[0033] "Countermeasure" – An action taken to prevent, minimize, or compensate for an SD event.

[0034] "Washout" – The diminishing capacity to appreciate continual motion at a constant rate.

[0035] "Threshold" – The level below which accelerations or motions are not sensed by the human vestibular system.

[0036] Threshold and Washout are significant factors in the onset of SD events. Within the relevant field of art, early research suggested the typical Threshold value for all axes could be Mulder's constant, two degrees per second. If a person experiences an acceleration of $1°/sec^2$ for one second, he or she will probably not sense that acceleration because the product (1°/sec) is below Mulder's constant. If the same acceleration occurs for three seconds however, it will likely be detected because the product (3°/sec) exceeds Mulder's constant. It should also be recognized that even a large acceleration of $10°/sec^2$ is unlikely to be felt if the duration is less than 0.2 seconds.

[0037] Mulder's constant, although helpful for general purposes has now been refined by Stapleford to reflect that the Threshold values are not uniform for all axes. As refined by Stapleford the general Threshold values are 3.2°/sec for roll, 2.6°/sec for pitch and 1.1°/sec for yaw. It is to be appreciated that acceleration may be linear acceleration and or rotational acceleration, and Washout can occur in either sense.

[0038] It is further important to note that not all humans have identical thresholds, however Mulder's constant is a good generalization. It is also important to note that not all acceleration durations above Mulder's constant will be sensed. Distractions, fatigue and other physiological reasons may exist to make the person oblivious to accelerations and/or durations that exceed Mulder's constant.

[0039] With respect to Washout, when one or more semicircular canals of the inner ear are put into motion, the fluid within the canal lags behind the accelerated canal walls. Lag of the fluid is sensed by hairs of the cupula and the brain interprets the movement of the hairs as motion in a direction. If motion continues at a constant rate for several seconds or longer, the fluid in the canals catches up with the canal walls and the brain receives the false impression that the turning has stopped, thus Washout has occurred.

[0040] It is important to note that Washout is non-linear. More specifically, FIG. 2 shows an exponential decay curve that represents the change in perceived rotation over time. In the exemplary case the subject is a pilot who has accelerated into a turn and reached a 5°/sec yaw rotation. At this point, the turn is held such that the rate of rotation is close to constant (i.e., there are no above-threshold accelerations for a period of time). After 2.5 seconds, the sense of rotation is down to about 2°/sec. With respect to the true 5°/sec yaw rotation, this is a 3°/sec difference between actual and perceived rotation, or a Washout of about 60%. Although described with respect to yaw, Washout may occur for pitch or roll, as well.

[0041] As is further set forth and described below, SD system **100** is used to identify and combat spatial disorientation in accordance with the following primary, but not exclusive, tenets:

> First – the SD system **100** acts to alert the subject with a countermeasure based on the probability of an SD event occurring, and the greater the probability, the more intense the countermeasure.
>
> Second – in determining the probability of an SD event, the SD system **100** accounts for Washout of the subject, a calculation that in at least one embodiment is non-linear.
>
> Third - the selectable countermeasures are multi sensory.
>
> Fourth – the SD system **100** is capable of identifying a predicted SD event as a vestibular illusion (e.g., somatogravic or somatogyral illusion), and even more specifically, identifying the specific type of illusion.
>
> Fifth – the SD system **100** permits both real time SD event determination and post-hoc analysis. With respect to aircraft flight for example, post hoc review permits researchers to simulate flight patterns and identify commonalities regarding SD events, thus permitting enhanced prediction of future SD events and evaluation of countermeasures applied to SD events.

[0042] Returning to FIG. 1, in at least one high level embodiment, SD system **100** includes an input routine **102**, a countermeasure routine **106** and an output routine **104**, each operably associated with a Vestibular Attitude Calculator (VAC) routine **108**. The VAC routine **108** further includes a threshold adjustment routine **110**, a Washout routine **112** and a vestibular illusion routine **114**.

[0043] The input routine **102** is operatively associated with at least one input device for receiving real time data, recorded data, subject preference information and/or combinations thereof. The real time or recorded data include environment data from an environment (e.g., an aircraft), including true position and orientation.

[0044] The real time or recorded data also include subject data from the subject within the environment. In at least one embodiment the received subject data include vestibular Threshold values and Washout timing values. Minimum rotation threshold values may also be provided. In addition, the Threshold and Washout values may be independently defined for each axis of rotation (yaw, pitch, roll), based on Mulder's constant, Stapleford values, or individual subject preferences. Moreover, the subject may provide data to modify the SD event illusion parameters so as to increase the effectiveness of SD system **100** in determining the probability of an SD event. Subject data may also include information such as the subject's name, date and time.

[0045] In addition, in at least one embodiment, subject data include information indicating the true position and orientation of the subject's head. For example, the commercially available helmets worn by fighter pilots typically include devices such as Polhemus motion tracking system, accelerometers, micro-electrical mechanical devices, or other devices that accurately measure and report the roll, pitch and yaw angles of the pilot's head. Private pilots, boat operators, divers, firefighters, astronauts or other subjects in other environments may be easily fitted with commercially available accelerometers or other micro-electrical mechanical devices to provide similar roll, pitch and yaw angles of the subject's head. It is to be understood and appreciated that the pitch, yaw and roll axes of the subjects head (i.e., the pilot) correspond to the same pitch, yaw and roll axes of the environment (i.e., the aircraft). Further still, subject data may also include data from the controls operable by the subject, e.g., flight stick and foot pedals.

[0046] Moreover, in at least one embodiment, the real time or recorded subject data are gathered from at least one device worn by the subject within the environment. In at least one alternative embodiment, the real time or recorded subject data are gathered from environment controls operable by the subject within the environment. In further addition, in at least one embodiment, the real time or recorded data also include external world data, including for example time of day, visibility and noise level.

[0047] The output routine **104** is operatively associated with at least one output device to provide the true position and orientation of the environment and the perceived subject attitude. Such output data may be stored for later use or post hoc review, and/or made immediately available to the subject within the environment or a remote operator of the SD system **100**. In at least one embodiment, the output routine **104** is coupled to a display and provides VCR-like controls (e.g., play, pause, stop, etc…), an attitude indicator and 3D animation of actual vs. perceived environment attitude.

[0048] The countermeasure routine **106** is operable to provide a multisensory approach to preventing, minimizing or compensating for subject SD. More specifically, the countermeasure routine **106** is operable to initiate a range of different countermeasures including visual, auditory, olfactory and tactile actions. As the probability of an SD event increases, the countermeasure routine **106** is also operable to increase the implemented countermeasure from cautionary (e.g., flashing a warning or sounding an alarm) to emergency (e.g., engaging autopilot or ejecting the pilot).

[0049] The Vestibular Attitude Calculator (VAC) routine **108** is operable to perform all calculations associated with the vestibular system including Threshold assessment of acceleration in each axis, vestibular Washout in each axis and perceived attitude deltas. This is accomplished in at least one embodiment through the Threshold adjustment routine **110**, the Washout routine **112** and the vestibular illusion routine **114**. In at least one embodiment the vestibular illusion routine includes a somatogravic routine **116** (predicting illusions caused by change in linear accelerations and decelerations or gravity that affect the otolith organs), and a somatogyral routine **118** (predicting illusions caused by angular accelerations and decelerations stimulating the semicircular canals).

[0050] So as to effectively and advantageously initiate the most appropriate countermeasure for a perceived SD event, SD system **100** is not only capable of determining the probability of an SD event occurring, but in at least one embodiment is also capable of selectively identifying at least three types of SD illusions, namely, the Leans illusion, the Coriolis illusion, and the Graveyard Spiral illusion. The probabilistic determination that a Leans, Coriolis or Graveyard Spiral illusion is occurring is based on time sequence modeling.

The Leans Illusion

[0051] The Leans illusion is one of the most common vestibular based disorientations, and is primarily associated with the erroneous perception of changes in bank angle. The Leans results from a subject's failure to detect angular roll or banking motion. During continuous straight and level motion, the subject will correctly perceive that he or she is straight and level. However, if a bank is entered slowly (below Threshold) or maintained for a prolonged time, the fluid in the semicircular canals of the ear will stabilize and Washout will occur. If the subject is quickly returned to straight and level, the motion of the fluid in the semicircular canals will give the sensation that the subject is banking in the opposite direction, and the subject will have a tendency to lean back towards the original bank orientation as an attitude erroneously perceived to be straight and level.

[0052] VAC routine **108** models the Leans illusion as a timed sequence of events with the probability of assessment of the disorientation increasing with each successive event. As indicated in FIG. 3, the first event **300** is the initiation of a roll at a rate below the vestibular threshold. Research investigating response to aircraft movements suggests that in at least one embodiment wherein the environment is an aircraft and the subject is a pilot, the default vestibular threshold values are 3.2°/sec for roll, 2.6°/sec for pitch and 1.1°/sec for yaw. The threshold adjustment routine permits these values to be adjusted for individual subjects. As shown in FIG. 3, the model is for the roll axis; however additional models exist for pitch and yaw as well.

[0053] The second event, **302** is a roll angle of greater than 5 degrees that lasts longer than 5 seconds. When the two events occur in sequence, it is possible that the pilot has not noticed the ensuing roll angle and as such that there is a difference between the subject's perceived attitude and the true attitude of the environment. As such the method indicates a possibility of an SD event, but only at a very low confidence level.

[0054] The third event **304** is the loss of altitude as measured by negative vertical velocity. In the model illustrated this is three hundred feet per minute, although this value is also adjustable. If this event follows events **300** and **302** in sequence, it is possible that the subject has not noticed the loss of altitude and the method represents an increased confidence in the assessment of the Leans.

[0055] The fourth event **306** is a roll well above the vestibular threshold in the opposite direction from that of the first event. If this occurs in sequence following events **300**, **302** and **304**, it is possible that the subject has noticed the roll angle and has quickly corrected back towards level. When this occurs, the subject's vestibular system registers a roll in the opposite direction, again resulting in a difference between the perceived attitude and the actual attitude of the environment. At this point the method represents a high level of SD event certainty.

[0056] The fifth and final event **308** is the tilt of the pilot's head opposite the perceived roll angle. If this occurs following events **300**, **302**, **304** and **306**, it is likely that the pilot is experiencing the Leans illusion and the model represents an even higher level of SD event certainty.

The Coriolis Illusion

[0057] The Coriolis illusion is the most dangerous of all vestibular illusions, causing overwhelming disorientation. The Coriolis illusion involves the simultaneous stimulation of two semicircular canals. It occurs when a subject experiencing a prolonged turn makes a sudden head motion in a different geometrical plane from the plane of the turn (such as by suddenly tilting the head forward or backwards).

[0058] When in a prolonged turn, the semicircular canal corresponding to the yaw axis will equalize. The endolymph fluid in the semicircular canals no longer deviates, or moves the cupula; thus the hairs of the cupula are not bent. If the person initiates a head movement in a geometrical plane other than that of the turn, the yaw axis semicircular canal is moved from the plane of rotation to a new plane of nonrotation. The fluid then slows in that canal, resulting in a sensation of a turn in the opposite direction of the original turn. Simultaneously, the other two canals are brought within a plane of rotation, the fluid stimulation in those other two canals creates the perception of motion in three different planes of rotation – yaw, pitch and roll – all at the same time.

[0059] When a person's head is suddenly tilted or moved in one direction or another, the brain usually is able to compensate very quickly with involuntary eye movement in the opposite direction. It is this behavior that permits a person to maintain visual fixation upon an object while his or her body is being jostled about. This typically helpful involuntary behavior can be a serious problem when experiencing the Coriolis illusion, for the subject may experience very rapid involuntary eye movement that further leads to feelings of disorientation. In addition, the involuntary eye motion often makes it impossible for the subject to visually perceive his or her actual orientation either from the horizon, instruments, or other objects. Visual warning systems or indicators are also effectively mooted during an episode of the Coriolis illusion.

[0060] Based on this description, an embodiment of the method employs a model of the Coriolis illusion as a time sequence of events that include the Washout effect on the vestibular system associated with the prolonged constant-rate turn. While the Coriolis illusion primarily occurs when Washout occurs in the yaw plane, the model also accounts for the potential for Washout in both pitch and roll.

[0061] More specifically, as shown in FIG. 4, the first event **400** is an above threshold acceleration in any of the three planes. The second event **402** requires that the acceleration from the first event **400** result in a sustained rate of rotation sufficient to induce Washout. Where the method is embodied in the SD system **100**, the Washout level is calculated by the VAC routine **108**. In at least one embodiment, the level of Washout achieved in the second event **402** is at least 50%. As shown in FIG. 4, the model is for the roll axis; however additional models exist for pitch and yaw as well.

[0062] The third event **404** is a large movement of the head in a plane other than the plane of acceleration while the conditions of the first and second events **400**, **402** are maintained. If this large motion of the head is detected, the probability of a Coriolis illusion occurring as an SD event is quite high. Although it is ideal to perceive the true orientation of the subject's head, such as when the subject is wearing a motion sensing helmet, the Coriolis illusion can also be predicted by observing awkward and/or radically inappropriate operations of the subject's controls and/or the attitude of the environment itself following the onset of the first and second events **400**, **402**.

<u>The Graveyard Spiral Illusion</u>

[0063] The Graveyard Spiral illusion is yet another somatogyral illusion commonly associated with fixed-wing aircraft. For example, the subject enters a turn (constant rotation) and remains in that turn for a sufficient time to induce Washout. This is then followed by correcting back to a straight and level path. The equalized fluid in the semicircular canals of the subject now moves in the opposite direction inducing a strong sensation of rotation in the opposite direction to the initial turn. To correct for this illusion the subject will then control the environment to correct for the perceived turn, an action that actually puts the environment back into the original rotation; however, the subject feels that he or she is traveling straight.

[0064] Based on this description, an embodiment of the method employs a model of the Graveyard Spiral illusion as a time sequence of events of rotations in the yaw axis. As shown in FIG. 5, the first event **500** is sustained rotation sufficient to result in a high level of Washout (e.g., 75%) in the yaw axis. This is then followed by the second event **502**, an above-threshold acceleration in the opposite direction – the standard action to end the original turn. The third action **504** is an above threshold yaw acceleration in the original direction prior to the subject recovering from the Washout effect, an event indicating a reasonable probability of an SD event. The model of FIG. 5 is for the yaw axis; however additional models exist for pitch and roll as well.

[0065] In the case where the environment is an aircraft, the fourth event **506** is negative vertical velocity while banked in the unperceived turn. Negative vertical velocity is the loss of altitude due to the loss of lift while in the unperceived turn. Such an event raises the probability of the SD event to yet a higher level of confidence. A fifth event **508** is the pitch up of the control inputs while banked, causing an increasingly tighter downward spiral.

[0066] This fifth event is due to the subject (e.g., pilot) feeling no rotation but being aware of the loss in altitude and pulling back on the stick. Were he or she in the perceived straight and level flight, this action would result in the environment (e.g., aircraft) climbing. As he or she is actually in a banked turn, pulling back on the stick places the environment (e.g., aircraft) into a tighter spiraling descent. This fifth event raises the probability of the SD event yet higher.

[0067] To advantageously predict with increasing confidence levels of the onset of vestibular illusions, in at least one embodiment, a state table is employed. More specifically, the VAC routine **108** of SD system **100** is associated with a state table. The state table maintains the state of the subject, the environment and the external world (if the method or system is collecting external world data), and permits the vestibular illusion routine (e.g., vestibular illusion routine **114**) to track the progression of events, such as those described above with respect to the Leans, Coriolis and Graveyard Spiral illusions. The state table may also be used to track the increasing confidence level that an SD event is occurring, and to determine whether the subject has responded to an initiated countermeasure.

[0068] Whereas prior systems, such as U.S. 5,269,848 to Repperger, use a specific threshold of difference between actual attitude and a Kalman filter model of attitude to determine whether an SD event is or is not occurring, the SD system **100** and disclosed method provides a sliding scale of confidence in predicting whether or not an SD event is occurring. Such a sliding scale of confidence prediction permits appropriate countermeasures to be implemented before a true crisis might develop, and for the implemented countermeasures to increase from cautionary to emergency as the probability of the SD event increases.

[0069] SD system **100** is advantageously operational either as an onboard system for combating spatial disorientation or as a post-hoc analysis tool. FIG. 6 illustrates a general high level flow diagram of an embodiment of a method applied onboard an environment, such as for example an aircraft, and FIG. 7 illustrates a general high level flow diagram of an embodiment of a method applied for post hoc review. It is understood and appreciated that the described processes need not be performed in the order in which they are herein described, but that this description is merely exemplary of at least one preferred method.

[0070] As illustrated in the real time detection environment of FIG. 6, in at least one embodiment, the method commences with the real time collection of environment data, block **600**. The environment data include the true position and orientation of the environment.

[0071] Real time data are also collected from the subject within the environment, block **602**. In at least one embodiment, the subject data include the true position and orientation of the subject, and more specifically the subject's head, within the environment. Subject modifiable parameters such as timing and Washout adjustments are in at least one embodiment established before activity in the environment (e.g., flight) commences.

[0072] In at least one embodiment, optional external world data are also collected as indicated by optional block **604**. Such external world data include time of day and visibility, and may include other information such as, for example, level of ambient noise or temperature. For example, a photo sensor may be used to determine whether it is bright and sunny, overcast or dark.

[0073] It is understood and appreciated that environment data, subject data and external world data are collected at regular time intervals. Such time intervals may be on the order of seconds or fractions of seconds such that the data appear as a continuous stream of data elements. Such data may also be collected at different intervals with the interval decreasing as the onset of events indicates the developing possibility of an SD event.

[0074] With respect to situations where the environment is an aircraft and the subject is a pilot, in at least one embodiment, the environment data are gathered from one location, such as the aircraft's center of gravity, and the subject data are received from a different location, such as where the pilot is sitting. As the pilot is typically located some distance away from the aircraft's center of gravity, the effects of roll, pitch and yaw upon the pilot are different from their effects upon the center of gravity of the aircraft.

[0075] The perceived attitude of the subject is then calculated for each increment of time for which there is collected environment data, block **606**. In addition, the Washout of the subject is also predicted. An evaluation is then performed collectively upon the environment data, the subject data, the perceived subject data and Washout timing, block **608**.

[0076] It is to be understood and appreciated that Washout, while important for some illusions, may be a non-factor for others such as the Leans illusion where it is the attitude changes below human threshold levels that are at issue. In such instances, the evaluation of Washout as effectively zero does not alter the prediction, as the environment data indicate the subtle onset of time sequence events that will identify the SD event.

[0077] More specifically, in at least one embodiment, the above models of the Leans, Coriolis and Graveyard Spiral illusions are employed. If the collected data indicate a probability for an SD event under any of these models, decision **610**, the method directs that countermeasure actions be taken. Of course, it is entirely within reason that the probability of an SD event is effectively zero. In such a case, the data are recorded for later use and post hoc analysis, block **612** (including at least environmental data and subject data). If the operations with the environment are continuing (e.g., still in flight), the method continues with the collection of data, returning to block **600**.

[0078] If, as in decision **610**, there is a probability of an SD event, the degree of probability, i.e., the certainty of the event, is evaluated in decision **614**. Where the probability is low, a cautionary countermeasure is implemented, block **616**. Such a cautionary countermeasure may include a warning light, auditory warning or other action selected to help inform the subject that an SD event may be occurring. Where the probability is high, decision **616**, a more intense countermeasure is initiated, such as an emergency countermeasure, block **618**.

[0079] With respect to the evaluation of data, block **608**, the collection of external world data in at least one embodiment advantageously improves calculation of the probability of an SD event. More specifically, in a setting where visibility is clear and the subject has visual awareness of the geography around him or her, and from that awareness a perception of his or her attitude and orientation, the vestibular illusions may be significantly thwarted by the subject's brain. The predictive method, such as that embodied by SD system **100** may therefore lower the prediction of an SD event in light of the external world data.

[0080] However, where visibility is limited and it is not possible to visually discern the surrounding geography, such as an when flying during overcast conditions or in haze, the predictive method, such as that embodied by SD system **100** may raise the prediction of an SD event in light of the external world data.

[0081] By predicting not only the probability of an SD event but also the type of SD event, the choice of countermeasure implemented to combat the SD event is advantageously improved. For example, if a subject is experiencing a Coriolis illusion, a blinking light or auditory alert will likely be of little value to the subject or the environment, whereas engaging autopilot or ejecting the subject may save either or both of the pilot and the aircraft. In addition, warning lights as countermeasures may have diminished effectiveness in a bright setting, just as auditory alerts may be diminished in loud settings. Likewise, in an increased G setting, tactile countermeasures may be masked or overshadowed by the forces already at play upon the pilot's body, thus making a strobe light or audio countermeasure more effective. The selectivity of different countermeasures, as well as the degree of the countermeasure (e.g., unique display symbol, blinking light to flashing strobe, audio warning to alarm siren to changing the pitch of a continuous artificial wind sound, activation of a warning signal to flashing messages across multiple displays, tactile sensations of temperature to blasts of cold air, tactile sensations of pressure or vibration (such as from a vest or seat) to electrical shock, mild to extreme odors, engaging auto-pilot or auto-recovery to automated ejection of the subject, recorded verbal requests to recorded verbal orders, etc…) permits the system to administer the most effective countermeasure or countermeasures so as to effectively combat the SD event.

[0082] In at least one embodiment, subject workload data are also received from the subject. Workload, as in what the subject is doing, may increase or decrease the subject's susceptibility to SD events and may alter the effectiveness of certain countermeasures. Human beings are capable of performing multiple tasks simultaneously; this ability is otherwise known as parallel processing.

[0083] In parallel processing, human beings use sensory channels, processing resources, and response channels (somatic, auditory, visual, vestibular, olfactory, psychomotor-primary, psychomotor-secondary and cognitive) used to greater or lesser degrees for different tasks. If the visual channels and auditory channels are in high use, such as when approaching for landing and communicating with the control tower, the subject pilot will likely respond more quickly to countermeasures administered to less involved channels, such as the olfactory or tactile. Moreover, in an embodiment utilizing subject workload data, countermeasures are further selected for non-taxed workload channels.

[0084] Whether based on external world data, workload data or combinations thereof, selectively choosing from a panel of countermeasures is advantageous. Selectively choosing from a panel of countermeasures including, but not limited to, auditory, visual, olfactory, tactile and mechanical intervention provides a significant advantage in providing at least one countermeasure with the highest likelihood of being acknowledged and acted upon by the subject in combating SD.

[0085] Following the implementation of a countermeasure, the data (including at least environmental data and subject data) are recorded for later use and post hoc analysis, block **612**. In at least one alternative embodiment, the perceived subject attitude is also recorded. If the operations with the environment are continuing (e.g., still in flight), the method continues with the collection of data, returning to block **600**. Such a return further aids in evaluating the effectiveness of the implemented countermeasure, blocks **616**, **618**. If the collected data again indicate the probability of an SD event, decision **610**, the countermeasure is continued, increased or augmented with additional countermeasures.

[0086] The analysis capabilities of the SD system **100** provide significant advancement in understanding SD events and devising further methods and systems to overcome them. For example, flight safety researchers can utilize the SD system **100** not only in accident reconstruction, but also to identify situations that might tend to induce or increase the opportunity for SD events to occur. FIG. 7 illustrates a high level embodiment of this post hoc review.

[0087] In order to act in a post hoc manner, environment data and subject data from a subject within the environment must be pre-recorded. As indicated in blocks **700**, **702**, these data are collected by the SD system **100**. Moreover, the stream of data may be read into a memory array, accessed sequentially or otherwise made available to the input routine **102** of SD system **100** as is appropriate for the physical embodiment of SD system **100** and the volume of data provided. In at least one embodiment, the subject Threshold values and Washout values, as well as the illusion model parameters, are also collected so as to enhance tailoring the post hoc review to a particular subject and or set of conditions, as indicated by optional block **704**.

[0088] To provide a sequence to the events, in at least one embodiment, the environment data are received as a series of distinct data elements, such as time-stamped data packets. Commencing with the first environment data element, the perceived subject attitude is calculated for the environment data element, block **706**.

[0089] In accordance with at least the above models (Leans, Coriolis and Graveyard Spiral illusion), the environment data, subject data and perceived subject attitude are evaluated to determine the probability of an SD event, block **708**. The probability as calculated is then reported to the SD system user performing the post hoc review, block **710**. In at least one embodiment, such a report is made via a display screen upon which the environment data, subject data, perceived subject attitude and probability of an SD event are graphically represented.

[0090] If the end of the environment data has been reached, decision **712**, the post hoc analysis process ends. If more elements of environment data remain, the process increments to the next element of environment data, block **714,** and re-calculates the perceived subject attitude, block **706**.

[0091] In at least one embodiment, the post hoc review process further includes a review of which countermeasures were initiated when the SD event was evaluated in real time, thus permitting the post hoc reviewer to evaluate the effectiveness of the countermeasures.

[0092] This post hoc review advantageously permits a researcher to identify similarities and differences between the collected data and similar pre-recorded event data. For example, flight patterns over certain geographic regions, or occurring at certain times of day or in certain types of weather may be identified as posing a greater risk of SD events to pilots. In at least one embodiment, this comparison review process may be incorporated as an automated component of the SD system **100**. In other words, when evaluating environment data, subject data and perceived attitude data in real time, an enhanced SD system **100** may also review similar data from pre-recorded events to further enhance the prediction of an SD event.

[0093] Changes may be made in the above methods, systems and structures without departing from the scope hereof. It should thus be noted that the matter contained in the above description and/or shown in the accompanying drawings should be interpreted as illustrative and not in a limiting sense. The following claims are intended to cover all generic and specific features described herein, as well as all statements of the scope of the present method, system and structure, which, as a matter of language, might be said to fall therebetween.

CLAIMS

WHAT IS CLAIMED IS:

1. A computer-readable medium on which is stored a computer program for detecting, analyzing and responding to a spatial disorientation event, the computer program comprising:
    - an input routine operatively associated with an input device for receiving real time data, recorded data, subject preference information or combinations thereof, the data including:
        - environment data from an environment, the environment data including true position and orientation of the environment; and
        - subject data from a subject within the environment;
    - a vestibular attitude calculator routine for computing the perceived subject attitude of the subject within the environment based on the environment data and subject data, the vestibular attitude calculator including:
        - a Washout routine to calculate a Washout value;
        - a vestibular illusion routine to calculate a probability of a vestibular illusion; and
        - a Threshold adjustment routine permitting adjustment of Washout thresholds and vestibular thresholds based on provided subject preference information;
    - a countermeasure routine operating in response to the Washout value and the probability of the vestibular illusion; and
    - an output routine operatively associated with an output device to provide the true position and orientation of the environment and the perceived subject attitude.

2. The computer-readable medium of claim 1, the Washout value being calculated as a non-linear element.
3. The computer-readable medium of claim 1, the input routine further including external world data.
4. The computer-readable medium of claim 1, wherein the countermeasure routine is operatively associated with a plurality of countermeasure devices, the choice and activation of a countermeasure determined by the Washout value, the probability of the vestibular illusion, and combinations thereof.
5. The computer-readable medium of claim 4, wherein the choice and activation of the countermeasure is further determined by the environment data.
6. The computer-readable medium of claim 1, wherein the computer program is executed to perform a post-hoc analysis of the subject within the environment.
7. The computer-readable medium of claim 1, wherein the environment is an aircraft in flight and the subject is a pilot.

8. The computer-readable medium of claim 1, wherein the vestibular attitude calculator further includes a workload calculator routine for calculating the workload of the subject within the environment.
9. The computer-readable medium of claim 1, wherein the subject data are recorded from at least one device worn by the subject.
10. The computer-readable medium of claim 1, wherein the subject data are recorded from one or more environment controls operable by the subject.
11. The computer-readable medium of claim 1, wherein the vestibular attitude calculator routine identifies the spatial disorientation event as either a somatogravic illusion or a somatogyral illusion.
12. The computer-readable medium of claim 11, wherein the somatogyral illusion is further identified as a Leans illusion, a Coriolis illusion or a Graveyard Spiral illusion.
13. The computer-readable medium of claim 11, wherein the countermeasure routine further operates in response to the identified spatial disorientation event.
14. A method for analyzing a spatial disorientation event post-hoc, comprising:
    collecting environment data elements recorded from an environment;
    collecting subject data recorded from a subject within the environment;
    calculating perceived subject attitude of the subject within the environment for each environment data element;
    evaluating the environment data, the subject data and the perceived subject attitude to determine a probability of a spatial disorientation event; and
    reporting the probability of the spatial disorientation event.
15. The method of claim 14, wherein the subject data are collected from at least one device worn by the subject.
16. The method of claim 14, wherein the subject data are collected from at least one environment control operable by the subject.
17. The method of claim 14, wherein the spatial disorientation event is identified as a vestibular illusion.
18. The method of claim 17, wherein the vestibular illusion is further identified as, a Leans illusion, a Coriolis illusion, or a Graveyard Spiral illusion.
19. The method of claim 14, wherein the environmental data are recorded at predetermined time intervals, the perceived subject attitude calculated for each time interval.
20. The method of claim 14, wherein the environment is an aircraft in flight and the subject is a pilot.
21. The method of claim 14, wherein post-hoc analysis includes determining any similarities or differences between the collected data and pre-recorded event data.
22. The method of claim 14, wherein the method is stored on a computer-readable medium as a computer program, which when executed by a computer will perform the steps of post-hoc spatial disorientation analysis.
23. A method for combating spatial disorientation, comprising:
    collecting real time environment data from an environment, the environment data including true position and orientation of the environment;
    collecting real time subject data from a subject within the environment;
    calculating perceived subject attitude of the subject within the environment for one or more environment data elements and predicting Washout;
    evaluating the environment data, the subject data, the perceived subject attitude and Washout to determine the probability of a spatial disorientation event and a type of spatial disorientation event;
    implementing, in response to the probability of a spatial disorientation event, at least one countermeasure, the countermeasure selectively chosen from a group of multi sensory countermeasures and countermeasure actions based on the environment data and spatial disorientation probability; and

recording the environmental data and subject data as event data for post-hoc review.

24. The method of claim 23, wherein the Washout is evaluated as a non-linear element.
25. The method of claim 23, further including collecting external world data, wherein evaluating includes evaluating the external world data to determine the probability of a spatial disorientation event.
26. The method of claim 23, wherein determining the probability of the spatial disorientation event includes identifying the spatial disorientation event as a vestibular illusion.
27. The method of claim 26, wherein the vestibular illusion is further identified as a Leans illusion, a Coriolis illusion, or a Graveyard Spiral illusion.
28. The method of claim 23, wherein the environment data are received from a first location within the environment and the subject data are received from a second location within the environment, the second location being different from the first location.
29. The method of claim 23, wherein the group of countermeasures includes auditory, visual, olfactory, tactile, auto-recovery, auto-ejection and combinations thereof.
30. The method of claim 23, further including receiving subject workload data from the subject within the environment, wherein implementing comprises implementing a countermeasure selected for a non-taxed workload channel.
31. The method of claim 23, wherein as the probability of a spatial disorientation event increases, the implemented countermeasure increases from a cautionary to an emergency countermeasure.
32. The method of claim 23, wherein the event data are stored with similar pre-recorded event data, post hoc review including determining similarities or differences between the event data and the pre-recorded event data.
33. The method of claim 23, wherein the method is stored on a computer-readable medium as a computer program, which when executed by a computer will perform the steps of real time and post-hoc spatial disorientation analysis.
34. A method for combating spatial disorientation, comprising:

collecting real time environment data from an environment, the environment data including true position and orientation of the environment;

collecting real time subject data from a subject within the environment;

comparing the collected data with pre-recorded event data to determine any similarities or differences between the event data and the pre-recorded event data and to predict subject response under similar environmental conditions;

calculating perceived subject attitude of the subject within the environment for one or more environment data elements and predicting Washout, the calculations including the predicted subject response;

evaluating the environment data, the subject data, the perceived subject attitude and Washout to determine a probability of a spatial disorientation event and a type of spatial disorientation event;

implementing, in response to the probability of a spatial disorientation event, at least one countermeasure, the countermeasure selectively chosen from a group of multi sensory countermeasures and countermeasure actions based on the environment data and the spatial disorientation probability; and

recording the environmental data and subject data as event data for post-hoc review.

35. The method of claim 34, wherein the Washout is evaluated as a non-linear element.
36. The method of claim 34, wherein determining the probability of the spatial disorientation event includes identifying the spatial disorientation event as a vestibular illusion.
37. The spatial method of claim 36, wherein the vestibular illusion is further identified as a Leans illusion, a Coriolis illusion, or a Graveyard Spiral illusion.
38. The method of claim 34, further including receiving subject workload data from the subject within the environment, the implemented countermeasure further selected for a non-taxed workload channel.

ABSTRACT

Provided is a spatial disorientation (SD) system and method for detecting, analyzing and responding to an SD event. An input routine includes receiving environment data and/or data from a subject within the environment, e.g., true position and orientation of the environment and/or subject. A vestibular attitude calculator computes perceived subject attitude for environment data elements, and may compute a Washout value. A vestibular illusion routine calculates the probability of a vestibular illusion. A threshold adjustment routine adjusts Washout and vestibular thresholds based on subject preference data. Probability and type of an SD event is determined by evaluating the received and computed data. Sensory countermeasures may be implemented responsive to the probability of an SD event. An output routine provides true position and orientation of the environment and perceived subject attitude via an output device; such information may be recorded for post-hoc review, a method of which is also provided.

METHOD FOR SPATIAL DISORIENTATION IDENTIFICATION, COUNTERMEASURES, AND ANALYSIS
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FIG. 1

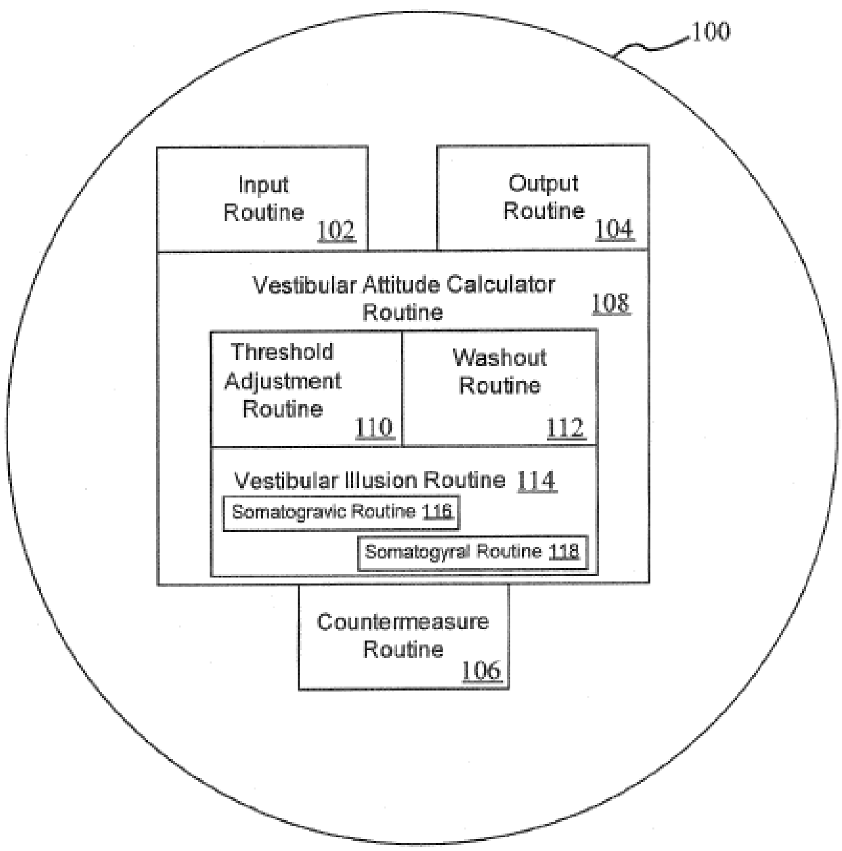

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FIG. 2

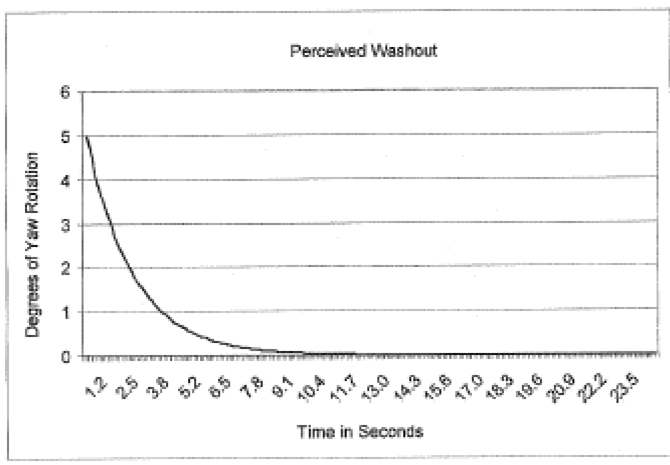

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FIG. 3

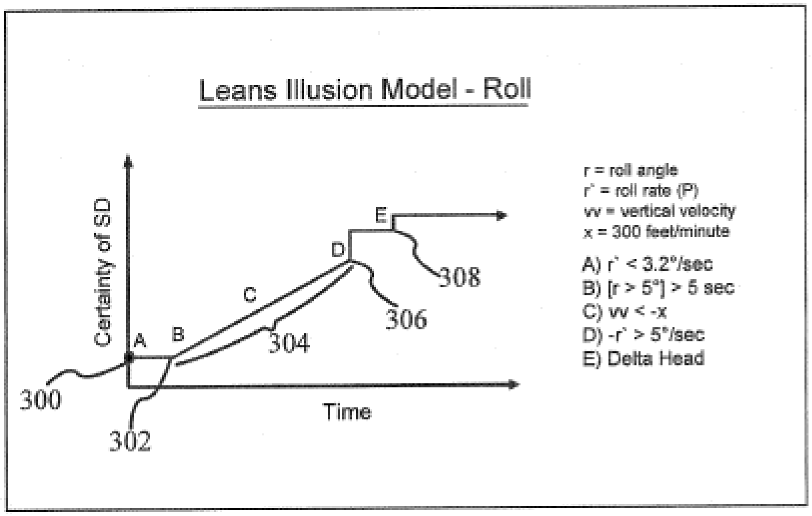

FIG. 4

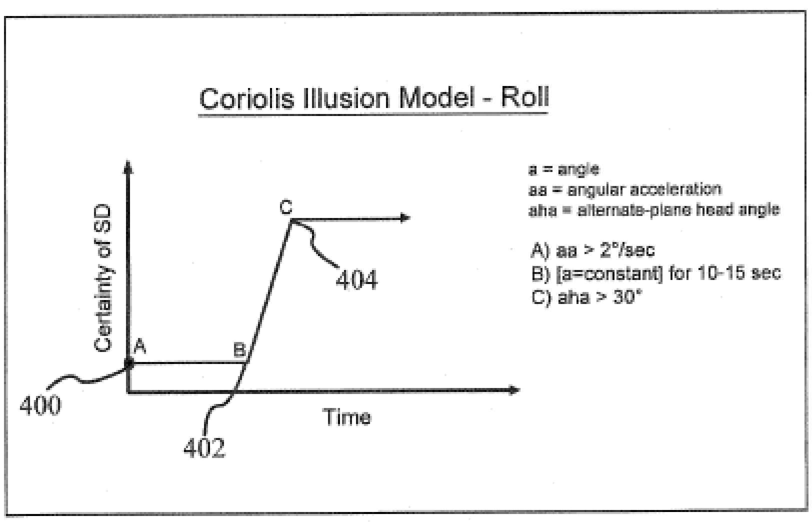

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FIG. 5

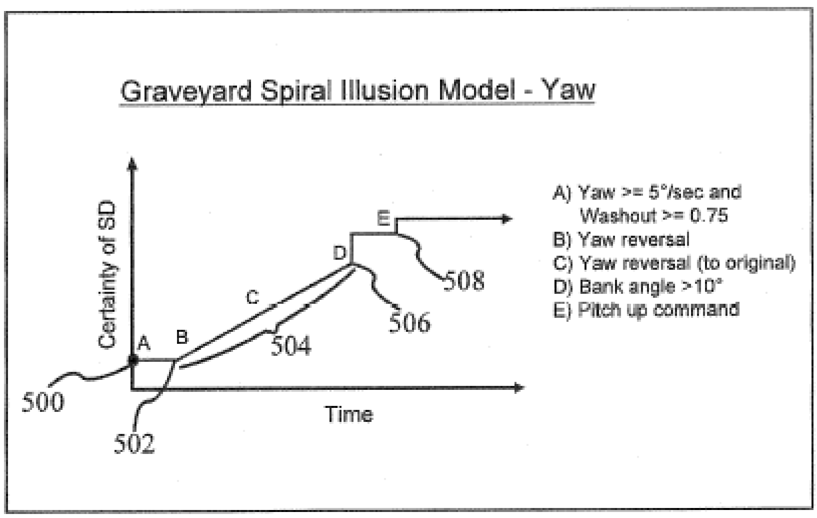

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FIG. 6

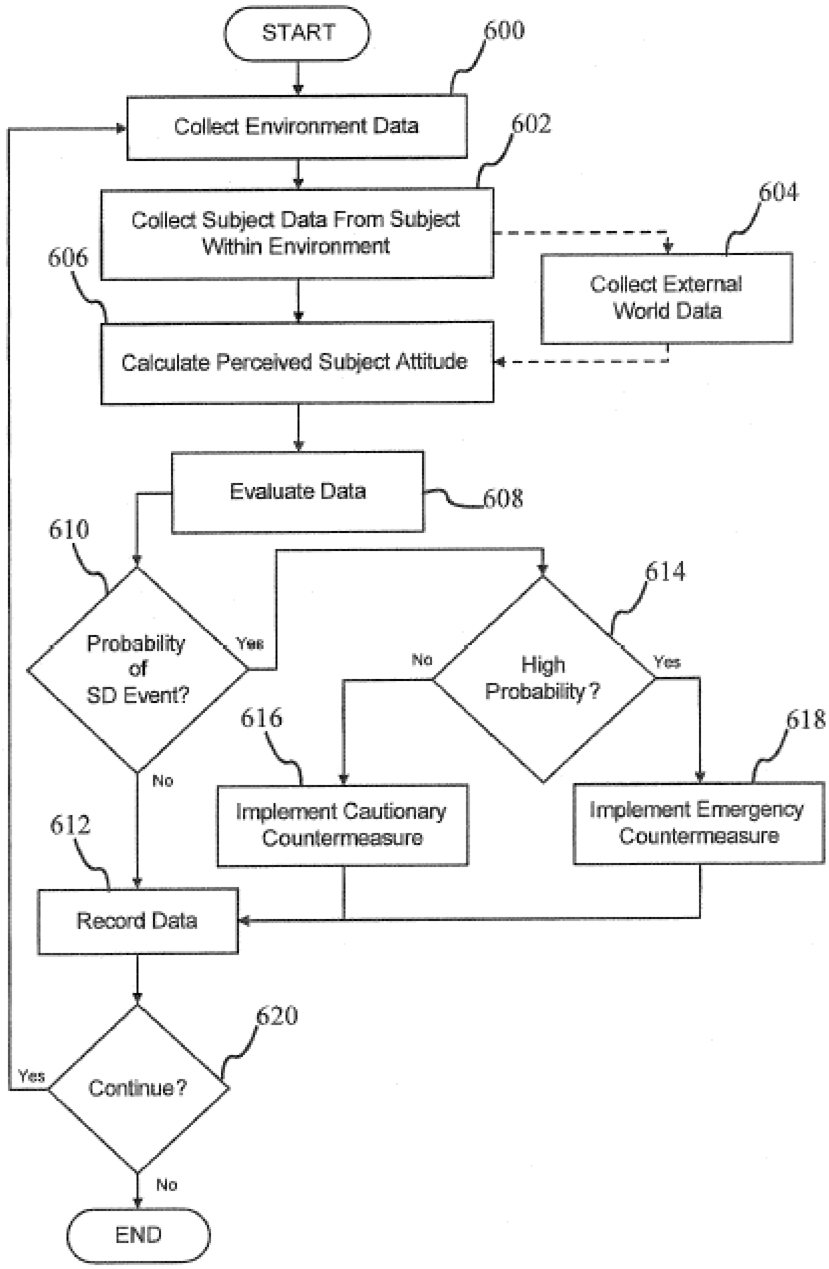

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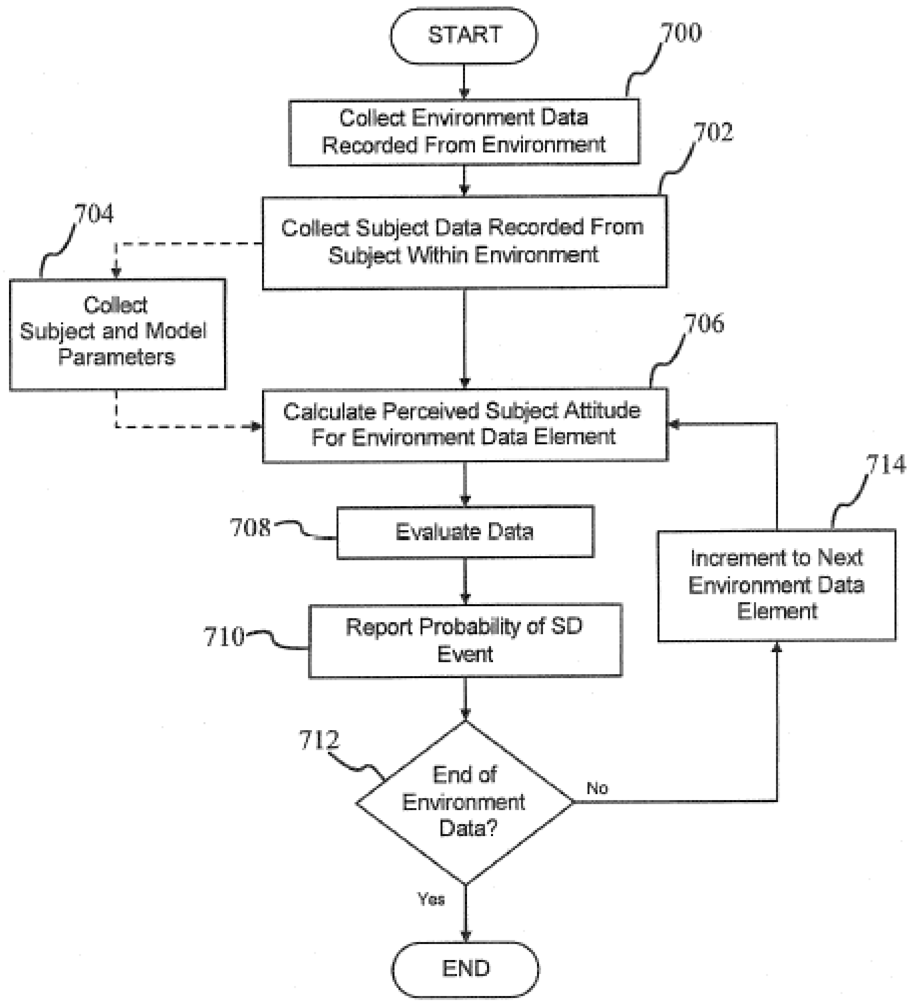
FIG. 7



Appendix D. Glossary

2D	two-dimensional
3D	three-dimensional
AC	aircraft
AFB	air force base
AFRL	Air Force Research Laboratory
AFSA	Air Force Safety Agency
AFSC	Air Force Safety Center
ASA	Aviation, Supplies, and Academics
AsMA	Aerospace Medical Association
ATC	air traffic control(ler)
CG	center of gravity
Class A	mishap that costs > $1M, or has loss of life, or causes permanent total disability, or destroys an aircraft
Class B	mishap that costs > $200K and < $1M, or permanent partial disability, or hospitalization of 3 or more people
Class C	mishap that costs > $20K and < $200K, or injury that results in lost work after the day or shift it occurred, or disability (source: http://www2.faa.gov/arp/environmental/5054a/MOAFINALVERSION.doc)
deg	degree(s)
F-15	USAF two-seat high performance fighter attack jet
F-16	USAF multi-role fighter jet
F-22	USAF's newest stealthy fighter attack jet
FAA	Federal Aviation Administration
F-PASS	Flight-Performance Assessment Standardized System (NTI's desk-top simulator and data collection tool)
FY	fiscal year
G, Gx, Gz	force due to gravity in particular axis, if specified
GAT-II	General Aviation Trainer, second generation – SD demonstration simulator
HDD	head-down display
HECI	Crew Systems Development Branch (part of HEC, the Crew System Interface Division, which is part of the Human Effectiveness Directorate, HE)
HUD	head-up display
Hz	Hertz (cycles per second; so, 2 Hz is 2 cycles per second)
ICD	interface control document
IFR	instrument flight rules
IMC	instrument meteorological conditions
IRB	institutional review board
MA&D	Micro Analysis & Design
MAAD	Micro Analysis & Design
mag	magnetic
min	minute(s)
MOD	Ministry of Defence (UK)
MRT	(Wickens') multiple resource theory
N/A	not applicable

NAMRL	Naval Aeromedical Research Laboratory
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
ONR	Office of Naval Research
PCT	Patent Cooperation Treaty
Perceived	Vestibular Attitude Calculator value for an attitude angle or motion
PPA	provisional patent application
R&D	research and development
SAVVOY	somatic, auditory, visual, vestibular, olfactory, psychomotor and cognitive workload scores
SBIR	Small Business Innovation Research
SD	spatial disorientation
SDAT	Spatial Disorientation Analysis Tool
sec	second(s)
SIB	Safety Investigation Board
SO	spatial orientation
SOAS	Spatial Orientation Aiding System
SoW	(contractual) Statement of Work
Type 1 SD	unrecognized SD
Type 2 SD	recognized SD
Type 3 SD	incapacitating SD
UAV	unmanned aerial vehicle
UK	United Kingdom (England)
US, U.S.	United States
USAF	United States Air Force
USAFA	USAF Academy
USD	unrecognized SD
VAC	Vestibular Attitude Calculator
VACP	visual, auditory, cognitive, psychomotor – resource components which comprise Wickens' multiple resource theory
VFR	visual flight rules
VMC	visual meteorological conditions