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ON LINE AND OFF-LINE TOOLS FOR PREVENTING AND ANALYZING VESTIBULAR SPATIAL DISORIENTATION MISHAPS: A SUMMARY OF THE ALION-MA&D / AIR FORCE RESEARCH PROGRAM

Christopher D. Wickens, Ronald L. Small, Alia M. Fisher, John W. Keller & Connie M. Socash

We describe a program of research and development to combat problems of in-flight spatial disorientation. One component is a computational model predicting the onset of the leans, the graveyard spiral, the Coriolis, and the somatogyral illusion, based on a vestibular model and inputs from the aircraft and control states. This model is validated in a flight simulation experiment. A second component we describe is the application of the model off line, embodied in a visualization and analysis tool for SD mishap investigation. A third component uses the model on-line, in flight to trigger visual, auditory, and tactile countermeasures to restore spatial orientation. The effectiveness of these countermeasures is demonstrated in two experiments.

Introduction

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, and the consequences of such accidents are tragically high (Holmes et al, 2003).

We describe below 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 analytical tool for mishap investigation, and as an on-line tool to restore spatial orientation in flight.

The overall structure of the system we have developed is represented in Figure 1. Here a pilot/aircraft system shown in the top box, is undergoing motion in 3D space which produces the experience of an illusion. Our system is designed to assess the nature and magnitude of the illusion in real time, using a set of *computational illusion models* as a basis for this assessment. If the illusion is assessed to be sufficiently serious, a set of *countermeasures* are implemented on the Interface, shown at the bottom. These countermeasures are designed, in one way or another, to restore orientation through corrective controls, and the loop is closed. Within the context of this closed loop structure, in sections below, we (1) discuss the vestibular model, (2) describe how the model was evaluated from experimental flight simulation data in a somatogyral illusion experiment, (3) describe how we applied the model to represent a series of aircraft mishaps through an analytic tool called SDAT (spatial disorientation analysis tool) and (4) examined how different interfaces could correct SD in experiments involving components of a system called SOAS (spatial orientation aiding system).

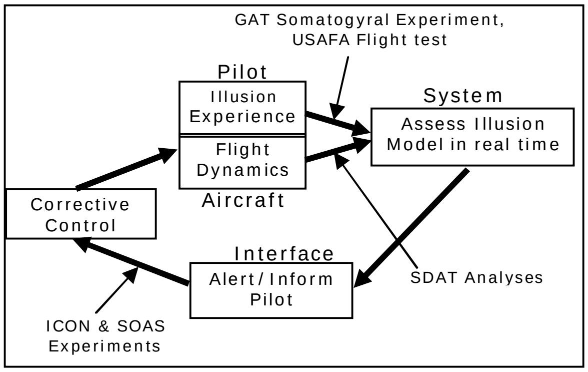

Figure 1. The spatial disorientation detection, analysis, and recovery system

The Vestibular Model & Its experimental Validation.

Following the classic work of Gillingham and others (1993; see also Previc and Ercoline, 2004), we have integrated the existing literature on the response of both the semi-circular canals, and the otolith organs (Guedry, 1974), 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, 2006). Particular emphasis has been placed on modeling four illusions: the leans, the graveyard spiral, the somatogravic illusion, and the Coriolis illusion.

The model works by accepting inputs of measurable accelerations and states within the cockpit, such as roll, roll rate, pitch, acceleration, as well as intentional aileron and elevator commands delivered to the flight stick. As shown with the example in Figure 2, the model looks for a particular profile of these inputs over time, which has been validated to generate an illusion type (here the Graveyard spiral; other profiles exist for other vestibular illusions). As time progresses and these different "markers" of the illusion are expressed, the model gains certainty that an illusory state exists.

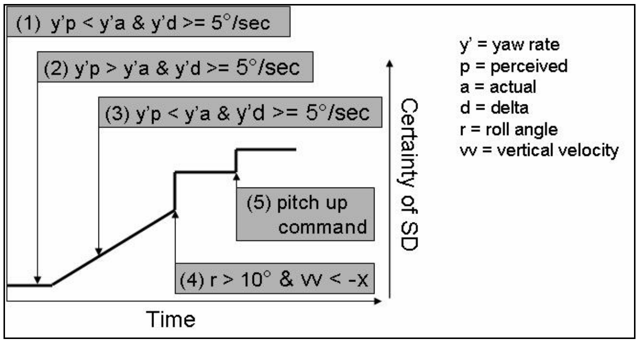

Figure 2. The graveyard spiral illusion sequence. Expressions within the grey boxes represents dynamic conditions which, if found to exist, trigger the corresponding phase of illusion build up.

In one experiment (Wickens et al, 2006), we examined the somatogyral illusion, and validated the model's ability to capture it, in a simulation at the US Air Force Academy, using their GAT simulator. Participants, both pilots and non-pilots, were subjected to the sustained rotations, typical of a rapid turn, or an even more rapid rotation experienced in a graveyard spiral. We examined both the magnitude of "washout" of the sense of rotation (as the semi-circular canals wash out), and, upon restoring a straight flight course, the sense of illusory counter-rotation. Participants rated their strength of experienced illusions across different spin rates and durations, and our model was able to predict these nine values, from the objective rotation data, with a correlation of 0.97.

Using the model for accident investigation: the SDAT tool.

In the experimental validation described above, the model was exercised with generated data from a controlled experiment, in which we could objectively measure the amount of illusion experience. In a very different sort of model test, we exercised the model with existing data from mishaps, in which we inferred spatial disorientation to be taking place. The system used to accomplish this is called SDAT (spatial disorientation analysis tool).

Mishap Analysis Approach. During the course of SDAT/SOAS R&D we received 12 mishap data sets from the Air Force, NTSB, and Navy; most (8 of 12) were from fatal accidents. In each case, we received the data set with little or no explanation about the accident; that is, we were sometimes told the aircraft type and perhaps whether or not the flight was at night, or an approach to a runway. In the case of the two NTSB data sets, we were given the full accident reports, but we purposely chose not to read the reports until after our analysis as a way to give ourselves a "blind" test.

First, we plotted the altitude, airspeed, heading, and other basic flight parameters from the digital data provided in order to give us a sense of the type of aircraft and flight profile we were analyzing. To prepare for SDAT runs, we put the data files in the needed format and ensured that there were no blank data cells. To fill-in any missing data, we used Excel's linear interpolation function. SDAT analyses consisted of running the properly formatted data file several times while varying the model parameters of the suspected illusion such as those shown in figure 2. This is a range of parameters for which a condition was true and hence a part of a sequence for which we were looking. When we found an illusion sequence that "persisted" across a range of different vestibular values, we considered the result to be reliable evidence of the pilot's experience. Alternatively, when we found an illusion sequence in only a narrow range of vestibular values, we did not give credence to that illusion having been experienced by the pilot.

Example Analysis. One of the most interesting analyses was of an NTSB accident data set where we found a Leans illusion that preceded the Graveyard Spiral that the NTSB concluded was the fatal plunge to the ground. In this accident, the aircraft lost electrical power, and SDAT found it likely that the pilot experienced the Leans right after that power loss, but about 2 minutes before the pilot entered the Graveyard Spiral. Figure 3 illustrates our findings. The NTSB was unaware of the Leans that preceded the Graveyard Spiral, but not surprised, since such an illusion sequence is not uncommon in general aviation accidents where fairly inexperienced pilots slowly lose control of their aircraft as they succumb to SD.

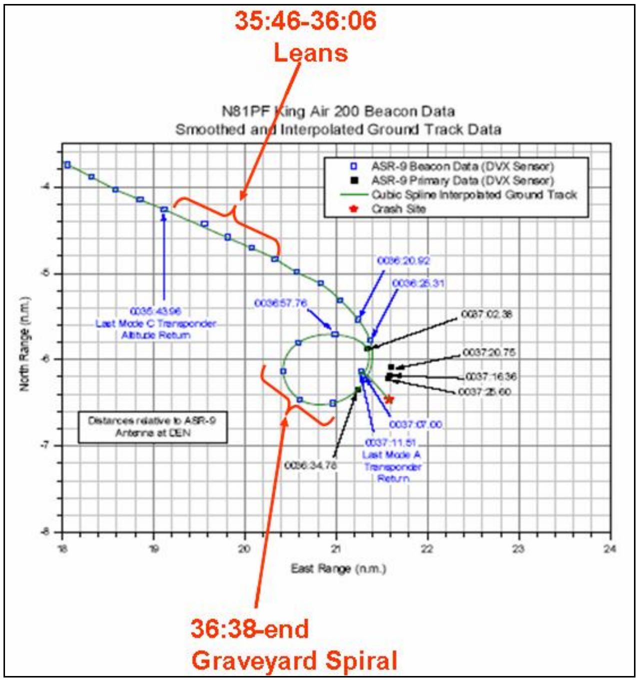

Figure 3. NTSB data set accident plot

General Results. To date, we have received a total of 12 mishap data sets: 9 from the Air Force, 2 from the NTSB, and 1 from the Navy. The initial 8 data sets from the Air Force had 2 that were clearly not related to vestibular SD, and so it would have been unrealistic to use SDAT to analyze those data sets. Of the remaining 6, the SDAT analyses provided useful results. Of equal importance to our R&D process is that we fine-tuned our SD illusion models thanks to the information gleaned from the mishap analyses. For example, we broadened our definitions of Leans and Graveyard Spiral. For the Leans, SDAT can detect it starting from straight and level flight, or from a steady banked turn. Similarly, a Graveyard Spiral can begin from a washed-out turn or straight flight.

Overall, 7 of 9 analyses (77.8%) provided useful results in terms of finding a vestibular illusion that the investigatory agency concluded was a factor in the mishap, or in terms of finding no vestibular illusion when the investigators also concluded that vestibular SD was not a factor. In many cases, SDAT revealed an SD problem that occurred prior to the SD illusion that led directly to the accident. That is, SD problems often happen in a series of worsening situations, and the final illusion is the only one "discovered" by investigators because the pilots do not survive to describe their whole experience. Such precursors may shed new light on accidents and may yield fruitful prevention strategies (e.g., training protocols, automated cockpit systems).

Note: It is important to emphasize that the above mishap analysis information is the opinion of the authors, only, and does not necessarily represent the views of any government agency or employee.

Using the model to close the loop: the SOAS Intervention Tool

As we have described above, the model can be implemented in the cockpit. Then, depending on the degree of inferred disorientation, graded interventions could be adaptively implemented to restore orientation. This is done through the SOAS (spatial orientation advisory system), a form of adaptive automation (Hammer & Small, 1995; Wickens & Hollands, 2000), in which the level of intrusiveness and compellingness of interventions is based upon the perceived seriousness of the disoriented state. The philosophy we have adopted here is that there is no need for aggressive interventions (e.g., taking control of the stick, loud voice commands) if the SD state is mild. Such more aggressive interventions should be implemented only if less aggressive ones are unsuccessful. Using data from attention research on the relative "compellingness" and intrusiveness of different modalities within which to impose command displays (control movement to recover from SD), we rank ordered a visual command (a pointing icon) to be less intrusive than either auditory or tactile directional commands. Choice between the latter two, if the illusion is serious, would be made based upon the ongoing level of auditory noise. A rendering of the cockpit flight deck environment where these intervention techniques were evaluated is shown in Figure 4.

Audio: Medium
Tactile: Medium
Audio Commands: No
Olfactory: No
Auto Recovery: No
Auto Ejection: No

Type: Leans
Confidence Level: Moderate
Trigger Event: Loss of Altitude
Aircraft State: SD Inducing Maneuver
Pilot State: S = None V = High A = Low O = Low V = Medium Y = High
Head Position: Pitch 0.23 Yaw 0.35 Roll 0.03

```
BeginningEffect: 25.24509 (Update Flight State (2))
EndingEffect: 25.35752 (Update Flight State (2))
BeginningEffect: 25.35752 (Update Flight State (2))
EndingEffect: 25.47013 (Update Flight State (2))
BeginningEffect: 25.47013 (Update Flight State (2))
EndingEffect: 25.56519 (Update Flight State (2))
BeginningEffect: 25.56519 (Update Flight State (2))
EndingEffect: 25.67963 (Update Flight State (2))
BeginningEffect: 25.67963 (Update Flight State (2))
EndingEffect: 25.7926 (Update Flight State (2))
```

Figure 4. Simulated cockpit display used to evaluate SOAS. The Icon is depicted on the HUD, commanding a mild right roll. The boxes to the right are not part of the pilot's display, but represent running parameters of the SOAS model, which would be responsible for triggering different countermeasures.

In one experiment using trained pilots at the US Air Force Academy (Wickens et al., in press), we examined the viability of a less intrusive HUD-located visual icon for such restoration. Pilots' simulated (fixed base) aircraft were positioned in various unusual attitudes, and we examined the speed of attitude recovery as a function of whether the icon was present or not. (See HUD display in Figure 4, for an example of the icon, which here is commanding a mild right bank. The presence of the icon significantly shortened response time, and reduced the frequency of inappropriate commands, relative to an unaided HUD.

In a second experiment (Wickens et al, submitted) we evaluated the viability of more intrusive voice and tactile interventions that are designed to be triggered if the icon fails to restore orientation. Here we observed a significant advantage of both a voice command display (e.g., "roll right") and a tactile command display (portraying a time-space flow across the body, in the direction of required correction), over the icon display, in the recovery from the more severe inverted attitudes.

Conclusions

Various components of the total system shown in Figure 1 have been successfully validated in our research. Our vestibular model can capture the magnitude of known disorientations in a flight simulator. In SDAT, the model can provide plausible accounting of the factors leading up to known mishaps, expressing these as the flow of events over time; and in SOAS, the intervention strategies are shown to be effective, the more intrusive ones (tactile and aural), selectively more so with the more severe disorientations. What remains missing at this time is an evaluation of the effectiveness of the full closed loop system operating in real time. Careful evaluation of this will be required to establish the value of the system in the cockpit. We believe we have laid the groundwork for such evaluation, and, in the mean time, its separate components have proven useful, particularly in understanding accidents and mishaps.

Acknowledgements

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