2015

Requirements for Developing the Model of Spatial Orientation into an Applied Cockpit Warning System

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Refinements have been made to a model of spatial disorientation (SD) to improve simulation of acceleration stimuli and visual-vestibular interactions. The improved model has been applied to aviation mishaps. The model is considered a technological countermeasure for SD because it is implemented as prototype software to aid the identification of mishap contributors in a way that should benefit didactic training. There is a more direct way this countermeasure can prevent SD, which is by adapting it for use as part of a cockpit warning system. The idea is to expand the model from one which explains mishaps post-hoc into one that warns pilots proactively whenever they are most likely to experience SD. This report introduces the general requirements that must be met to successfully expand the model for use as a proactive cockpit warning system, as well as the key criteria for determining whether it is effective.

As part of a recent U.S. Army Medical Research and Materiel Command effort, considerable refinements were made to the existing mathematical model of spatial disorientation (SD), to the point where it can analyze laboratory and in-flight acceleration stimuli and mishaps that were not feasible to analyze previously, can simulate the integration of visual-vestibular inputs better than before, and can compare the predictions from multiple theoretical models (Newman et al., 2012; McGrath, in Lawson et al., 2014; McGrath et al., 2015). These improvements constitute a technological countermeasure for SD in the sense that they have been implemented as software to improve our understanding of the specific, quantitative, and proximal factors that cause mishaps. This can have positive repercussions for aviation training. However, there is a much more direct way that this type of technological countermeasure can prevent SD, which is by developing it for use as a cockpit warning system. The idea is to adapt the same model presently used to determine whether the moment-by-moment vestibular and visual cues present prior to a flight mishap could have caused a specific disorientation illusion. This model would be refined to, instead, proactively warn pilots whenever their current vestibular and visual cues in-flight are likely to cause a specific disorientation illusion. This report introduces the general requirements such a system would need to meet and the features it must have in order to be successful. The four main requirements that must be met in order to expand the current model into an accurate cockpit display or warning system are as follows: 1) model outputs to the display must incorporate inputs concerning the state of the human user; 2) model outputs to the display must incorporate inputs concerning the state of the system within which the user must operate (i.e., the aircraft and its surrounding environment); 3) the interface (displays and controls) must be user-friendly to pilots; and 4) the usefulness of the new display must be verified during flight testing. These general requirements are elaborated in Table 1, which lists the critical and the desirable inputs and improvements needed to develop the current quantitative vestibular orientation model into a real-time, in-cockpit display or warning system.

Table 1.

Key requirements or aspects of a cockpit display based on the orientation-model.

	1: Knowing Pilot State	2: Knowing System State	3: Usability	4: Efficacy
Critical Aspects	1A. Model-display system must "know" the pilot's control inputs	2A. System must know state of the aircraft (attitude, acceleration, etc.)	Pilot-friendly user interface	Efficacy verified in-flight[1]
	1B. System must know whether pilot is looking at primary flight displays	2B. Must know environmental visibility		
Desirable Aspects	1C. Know whether pilot is cognitively attending to instruments	2C. Know flight instructions or clearances		
	1D. Know pilot's head position and motion			

Critical Pilot State Requirement #1A: Knowing the Pilot's Control Inputs

The current model is designed to explain proximal, perceptual causes of SD mishaps after the event has occurred by determining when a pilot is likely to have been disoriented and what his or her misperception was (e.g., direction of felt pitch and/or roll) during the disorientation episode. This is accomplished by comparing the quantitative predictions the model makes concerning the pilot's perceived orientation (during each second preceding a mishap) to the pilot's actual orientation (derived from the outputs of the flight data recorder), and then determining whether there is a mismatch between the two, and if so, whether the pilot's joystick control inputs at the time of comparison are consistent with the mismatch, which would imply the presence of a perceptual illusion[2]. For example, when a pilot takes off from the ground with sufficient forward acceleration and enters a cloud layer, he may experience an illusion of being pitched backward more than is actually the case (Figure 1). This is due to the well-known *somatogravic illusion*, in which the pilot perceives the direction of "down" to be dependent not solely upon the direction of gravity, but rather, the direction of the resultant between gravity and the aircraft's forward acceleration, known as the gravitoinertial force. This gravitoinertial force gives the pilot the illusion of still being pitched back when the aircraft already has leveled off; thus causing the pilot to unnecessarily move the stick forward to level off, which can result in an unrecognized dive towards the ground. Many mishaps have been attributed to the somatogravic illusion, and variants of the illusion can occur during prolonged banking turns and other maneuvers (Newman et al., 2012; McGrath, in Lawson et al., 2014; McGrath et al., 2015). The occurrence and severity of the illusion can be accurately modeled with the current orientation model based on the way that acceleration inputs to the aircraft would be processed by the vestibular system, but the model user then has to compare the model's outputs manually to the pilot's control input data to determine if there was a discrepancy.

If the present orientation model is to be used to drive a real-time cockpit display, it must receive stick inputs from the pilot and compare these automatically to the model's moment-by-moment prediction of the pilot's perceived orientation. In the somatogravic example provided in Figure 1, the model should know when the pilot is pushing the stick forward in a manner that accords with the illusion of not being leveled off yet, but does not accord with reality of already being leveled off. Fortunately, joystick inputs by the pilot are already available as data the model can acquire. This is not so for every aspect of the pilot's state that the model needs to know, however, as described below.

[1] The criteria for deciding if the display is effective are discussed later in this report and summarized in Table 2.

[2] This approach assumes the pilot has not intentionally flown the aircraft into the ground, which can usually be verified by the voice recording.

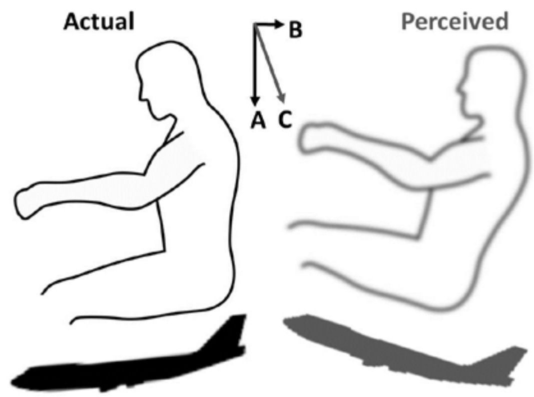

Figure 1. In this example of a somatogravic illusion, Earth's gravitational force (A) combines with the force caused by forward acceleration during take-off (B) to yield a resultant force (C) that makes the pilot feel that "down" is behind him, causing him to perceive pitch backwards (gray, right) rather than his actual orientation (black, left).

Critical Requirement #1B: Knowing if the Pilot is Looking at the Instruments

The orientation model assumes that SD usually occurs when the pilot is unable to see the outside world and has failed to continually maintain an accurate mental model of aircraft orientation by referencing the flight instruments. During mishap investigations using the model, it often must be assumed that the pilot was not attending to the instruments because the pilot's actual direction of gaze is not known. Inferences are made based on the phase of flight, the atmospheric conditions, and the voice record (e.g., indications that attempts at visual flight were made when a switch to instrument flight was warranted, indications that workload, stress, and distraction were high due to aircraft troubleshooting, navigation, or communication problems). It would be better for mishap investigation if the pilot's direction of gaze was known, and this information would aid the development of a cockpit display based on the orientation model. Direction of gaze can be inferred readily via videooculography (Stephane, 2012, in Boy. Ed.). Some aircraft systems track the pilot's head orientation, but no current systems track gaze. Since direction of gaze can vary considerably relative to head orientation, gaze data is needed to improve post-mishap reconstruction and to permit the model to become a perceived-versus-actual orientation display and/or a disorientation warning system. Suitable technology exists to fulfill this requirement and software parameters could be adjusted readily.

Desirable Aspect #1C: Knowing if the Pilot's Cognitive Attention is on the Instruments

Most of the time, tracking the pilot's gaze and knowing if it is dwelling frequently upon the primary flight displays will be sufficient to know that proper instrument flight is being maintained. Under certain circumstances, it is possible for the pilot to fix his gaze upon the instruments without cognitively attending to and processing the symbolic information provided (Mack, 2003). This can occur when a drowsy pilot stares in the direction of the instruments without cognitively processing the information provided. It can also occur when an overworked or highly stressed pilot looks at the instruments habitually without sufficient engagement of attention and working memory. Every reader will recall a time when he or she was driving an automobile and looked at a vehicle display, but then had to look again to cognitively register the information. While such cognitive lapses are not frequent, it is nevertheless true that a disorientation cockpit warning system would be more accurate if it knew not only whether the pilot was looking regularly at the instruments, but also whether the pilot was in a cognitive state that prevented the information from being processed. This goal might be achieved by collecting physiological data, e.g., to distinguish when brain activity during visual fixation is consistent with paying attention to the display or, rather, indicative of gross under- or over-arousal that generally degrades attention, or a more specific case of inattentional blindness (Turatto et al., 2002; Mack, 2003). Similarly, additional parameters of gaze could be monitored (such as saccadic velocity, fixation dwell time between saccades, number of saccades, and pupil diameter) to determine the pilot's state of arousal. Such instrumentation requires its own cycle of development and validation, however. Since arousal state information is not fully mature for cockpit adoption yet and gaze information should be sufficient, arousal state information is considered desirable in the future but not critical presently.

Desirable Aspect #1D: Knowing the Pilot's Head Position

It has long been known that making head movements during banking turns in flight is disorienting. This was initially thought to be due to the vestibular effects of simultaneous multi-axis head rotation (known as Coriolis cross-coupling), but it is now believed that the disorienting effect derives mostly from the unusually large amplitude and velocity of the otolith organs during high G head movements (known as the G-excess effect, Rupert & Guedry, 1991). The current model can predict Coriolis cross-coupling and G-excess effects, but to do so, it must know the pilot's head position and motion. Once the two critical pilot state requirements of the new display are met (#1A-1B), this readily-added capability should be incorporated. Current technology is suitable for this purpose.

Critical System State Requirement #2A: Knowing the Position and Motion of the Aircraft

To make predictions about the perceived orientation and motion of the pilot, the user inputs flight parameter data (attitude, altitude, acceleration, etc.) into the model. The model then processes these data according to the known functioning (e.g., time constants) and limitations of the vestibular organs in order to compute actual versus perceived orientation of the pilot and aircraft. The needed data is already available from many aircraft. The model is already equipped to upload and process such data, but it presently does not do so in real-time. Software parameters can be modified readily for this purpose.

Critical Requirement #2B: Knowing whether the Outside World is Visible

Currently, the model user must infer from independent information (e.g., the draft mishap report) whether visibility outside the aircraft was compromised and whether the pilot was not processing symbolic orientation information from the primary flight instruments. Common contributors to SD include unaided night flight or flight into a degraded visual environment, especially when there is high workload or distraction and the gravitoinertial force vector does not match the "down" given by gravity. For the model to become a disorientation warning system, it should know in real-time whether the pilot is not likely to be able to see the outside world sufficiently to fly under visual flight rules. This could be accomplished via the US Army Aeromedical Research Laboratory's airborne visibility indicator (Estrada et al., 2004) that could be utilized to send automated updates to the model concerning flight visibility. Model software parameters could be adjusted readily when the airborne indicator indicates that outside visual information is unreliable.

Desirable Aspect #2C: Knowing the Flight Instructions and Clearances

In the simple somatogravic example explained in Figure 1, it would be advantageous if the model knew that the pilot's intention was to fly straight-and-level once he or she had reached a certain altitude. This would help the model confirm that pilot's control inputs and aircraft motions were not only consistent with the aforementioned backward pitch illusion, but also in violation of the pilot's plan to level-off. Other aspects of the flight clearance instructions that could be input into the model include the maximum bank angle during a turn, the minimum and maximum altitude during the flight phase, etc. These inputs are listed as desirable future information for the display rather than information that is critical currently. This is because spatial disorientation usually can be inferred without this information and because certain aspects of the flight instructions and clearances for certain military missions may be too complicated or flexible to permit easy designation and incorporation into the model. Such information is readily available during many military transport operations and commercial civil airlines flights, however.

Requirement #3: A Pilot-Friendly Display

The model incorporates a convenient graphical user interface (GUI) that allows the user to select model parameters and see animations of actual versus perceived (predicted) orientation during the time leading into a mishap. However, the GUI and the virtual control buttons for altering model parameters are designed for the use of spatial orientation specialists working in an office environment. Modifications will be necessary for in-cockpit use by pilots. First, the display should conform with general vehicle display principles (Berson et al., 1981; Mejdal et al., 2001; Wickens & Carswell, 2006). Second, it should be tailored to pilots rather than orientation experts.

Requirement #4: An Effective Display

Once all the necessary elements for a model-based disorientation display are assembled and integrated, it is critical to test them in flight to confirm that the display is effective. Before such tests are done, the criteria for an effective display must be established. A few key criteria are shown in Table 2. Further detailing and prioritization of these criteria will yield a correct decision concerning whether the display is useful in maintaining situation awareness and aircraft control, or instead requires further modification.

Table 2.

Criteria for verifying the efficacy of an orientation- model-based cockpit display.

Operational Criteria	Human Factors Criteria	Scientific Criteria
Identifies the most hazardous and common types of SD	Provides salient information	Yields few false positive warnings (false threat warnings)
Prevents full entry into SD during disorientating flight maneuvers	Provides clear information	Yields almost no false negatives (failures to warn of real threats)
Permits rapid recovery after being placed into an unusual attitude		

The first operational goal mentioned in Table 2 is to develop the orientation model into an applied cockpit warning system that will be able to predict the most hazardous and prevalent SD illusions. Some key types of SD illusions with a vestibular component that are mentioned in prominent aeromedical textbooks (Rainford & Gradwell, Eds., 2006; DeHart & Davis, 2002) and key reviews (Previc & Ercoline, 2004) include: the leans, undetected (helicopter) drift, false/sloping horizon, tumbling/vertigo, graveyard spiral/spin, somatogravic illusion, inversion illusion, somatogyral illusion, elevator illusion, G-excess illusion, and vection. This list is not exhaustive, but covers most of the vestibular or visual-vestibular illusions most commonly noted by pilots. It is difficult to know which illusions are most deadly. Among these illusions, some tend to be mentioned less frequently as mishap contributors while others are frequently identified as factors in deadly mishaps. To the extent that more-frequent mention in class A mishap reports reflects how dangerous a given SD illusion is, we can conjecture that illusions such as the somatogravic illusion and undetected helicopter drift are particularly dangerous and should be included in the model-based cockpit warning system. Similarly, we infer that unrecognized (type 1) SD is inherently more dangerous than recognized SD, which would mean that tumbling/vertigo may not have to be included in the cockpit display if it cannot be modeled adequately. Currently, the model can predict over a dozen orientation illusions. Among these, we are most confident in the model's ability to predict in-flight cases of somatogravic illusion, inversion illusion, undetected drift, visual illusions that involve a vection component (e.g., induced by dust blowing during helicopter landing), and the occurrence of the leans. The model will require modifications to accurately predict variations in the duration of the leans. Once head-movement data are available, the model will be able to determine the intensity of head movement-contingent illusions such as the dynamic G-excess illusion or Coriolis cross-coupling (Rupert & Guedry, 1991). These and other modifications are being worked on as part of the Program Executive Office Aviation's Small Business Innovative Research efforts.

Possible Characteristics and Applications of the Display

The envisioned cockpit warning system would take in data from a variety of onboard sources that monitor the motion of the pilot and aircraft (e.g., attitude and heading reference system, accelerometers, gyroscopes, and head and eye position). Data from each source would be converted to the correct sensory coordinate frame and used as inputs to drive the orientation model. The model would process the sensory data in real-time and output a continuous prediction of the pilot's estimated orientation and perceived self motion. This prediction could be used for three related, in-cockpit uses. First, its outputs could augment visual displays by showing the pilot's perceived direction of "down" vs. the actual direction of down (e.g., via a simplification of Figure 1). Second, it could drive an auditory warning system that would identify when the pilot is entering a flight condition that is likely to induce SD and alert the pilot (e.g., in the situation depicted in Figure 1, the warning might say "possible illusion of backward pitch: check instruments!"). Third, in cases where continuous information is not already being provided to the pilot via a tactile situation awareness system, the disorientation display could trigger a strong vibrotactile cue on the body providing the actual orientation of down. For example, in Figure 1, a seat vibration could be triggered under both thighs and well forward of the misleading pressure cues the pilot is getting on his buttock and lower back.

Acknowledgements

We thank Ms. Linda-Brooke Thompson for assistance with the preparation of this manuscript. This report is solely the opinion of the authors and does not reflect official opinions or policies of the U.S. Government nor any part thereof. Use of any trade names does not imply endorsement of products by the U.S. Government nor any part thereof. Mention of any persons or agencies does not imply their endorsement of this report.

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