TITLE: Analysis of Spatial Disorientation Mishaps in the US Navy

TITLE: Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures [Desorientation spaiale dans les vehicules militaires: causes, consequences et remedes]

Analysis of Spatial Disorientation Mishaps in the US Navy

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Summary

Spatial disorientation (SD) and subsequent loss of situation awareness (LSA) mishaps for military air forces, commercial aviation, and general aviation have an estimated annual cost in the billions of dollars. SD occurs when the pilot has an incorrect perception of the attitude, altitude, or motion of one's own aircraft relative to the earth or other significant objects. One example of the devastating effects of SD is the following mishap: A US Navy F-14 Tomcat, shortly after take off, crashed into a residential neighborhood destroying several homes and killing the two aircrew and three people on the ground. Causal factors in the mishap included SD and cockpit distraction. The Naval Aerospace Medical Research Laboratory (NAMRL) has developed an SD mishap analysis tool to support US Navy mishap boards in their investigations, to provide insight into the problem of SD in naval aviation, and to train aviators to avoid SD mishaps. The SD mishap analysis tool uses spatial orientation models and computer animation techniques to produce three-dimensional (3-D) computer simulations of SD mishaps.

Using mishap data from flight data recorders, eyewitness accounts, radar transcripts, and videotapes, an estimate of the mishap pilot's spatial orientation perception is calculated using spatial orientation models. These spatial orientation models are based on current literature and additional data from centrifuge, aircraft experiments, and aircraft mishaps gathered at NAMRL over the previous 40 years. The estimated perceived pilot orientation, along with computer models of the actual aircraft attitude and altitude, flight data, and actual pilot position, are then used to develop a 3-D computer simulation of the SD mishap under consideration. The current spatial orientation models used in the SD mishap analysis tool are adequate to address many types of mishaps, including mishaps due to the somatogravic illusion. However, the current spatial orientation models do not provide accurate results for some types of SD mishaps. Further research and development is required to enhance the mishap analysis tool to provide accurate descriptions of pilots' perceptions in the full range of US Navy aviation environments.

The SD mishap analysis system provides an intuitive tool that permits visualization of a complex problem. In the previous five years, results from these analyses have been used in mishap board reports, Judge Advocate General (JAG) investigations, congressional hearings, and television news reports.

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Introduction

Spatial disorientation (SD) and the subsequent loss of situation awareness account for a significant percentage of mishaps in aviation. As aircraft have become more reliable and safer from a mechanical perspective, the proportion of human-related mishaps has increased. Based on accident rates for the United States (US) Air Force, Navy, and Army, SD mishaps result in the loss of 40 lives on average per year (Gillingham, 1992; Matthews and Gregory, 1999; Braithwaite, Groh, and Alvarez, 1997). The cost of SD mishaps also includes mission failure, the impairment of mission effectiveness, and the monetary value of aircraft and equipment loss. Considering the number of military air forces, commercial and general aviation, the estimated annual material cost of SD mishaps is in the billions of dollars (Gillingham, 1992). In today's military aviation, there is an added emphasis on night flying, all weather capability, and low altitude missions which are all factors that increase spatial disorientation.

The safety of the aircraft and the ability to perform the aircraft's mission are highly dependent on the pilot having an accurate awareness of the current situation, including the state of one's own aircraft, mission goals, external conditions, other aircraft, and external hostile factors. The first and critical step in acquiring and maintaining situation awareness is to perceive the status, attributes, and dynamics of elements in the environment (Figure 1, shaded region, Endsley, 1995). In aviation, a pilot usually perceives elements such as aircraft attitude, altitude, or motion relative to the earth or other significant objects. SD occurs when the pilot has an incorrect perception of the attitude, altitude, or motion of one's own aircraft relative to the earth or other significant objects. This corresponds to an inaccurate perception of the elements in the current situation.

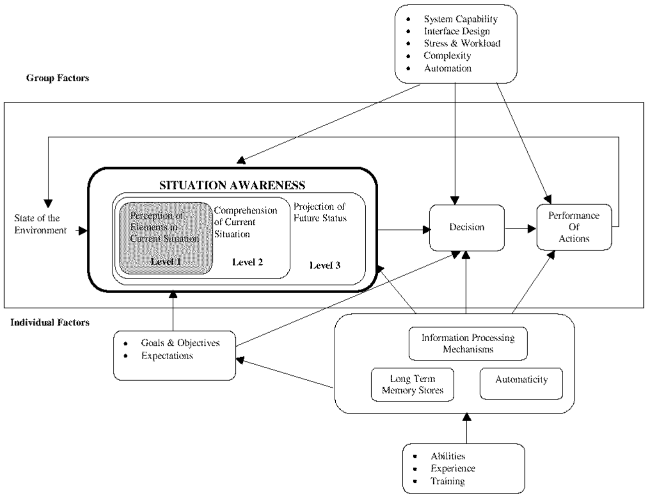


***Figure 1:** Model of situation awareness (from Endsley, 1995).*

SD mishaps have occurred ever since the terrestrial human entered the dynamic 3-D aeronautical environment. As long as early aviators could maintain clear visual reference with respect to the ground or horizon, orientation did not pose a significant problem. However, "cloud flying" and other forms of flight in reduced visibility claimed many early aviators' lives (Ocker and Crane, 1932). The incidence of SD mishaps declined when pilots began to receive the appropriate training in the correct use of aircraft instruments, including the attitude indicator and the turn indicator (Stark, 1935). However, SD mishaps were not eliminated completely, because the attitude indicator is a visual instrument, and only provides orientation information when the aviator repeatedly looks at the instrument for sufficient time to see and cognitively process the information.

In our day-to-day terrestrial dynamic activities, spatial orientation is continuously maintained by accurate information from three independent, redundant, and concordant sensory systems; the visual system, the vestibular system, and the somatosensory system (skin, joint, and muscle sensors). These complementary and reliable sources of information are integrated in the central nervous system to maintain accurate spatial orientation awareness during static and ambulatory terrestrial conditions.

In the aeronautical environment, however, the vestibular and somatosensory systems no longer provide reliable information concerning the magnitude or direction of the gravity vector or "down" (Figure 2). During aircraft maneuvers, the almost continuous changes in aircraft acceleration expose aircrew to a resultant gravito-inertial force that is constantly changing in magnitude and direction. Under such circumstances, somatosensory and vestibular information concerning the direction of "down" will be inaccurate, and increased reliance must be placed on visual information if spatial orientation is to be maintained. Currently, the only reliable information is that obtained visually. Furthermore, the varying gravito-inertial force fields, misleading visual information and prolonged rotations can produce illusions of motion and position (see Benson, 1999 for a complete description of SD illusions). Thus the central nervous system, which on the ground normally integrates continuous accurate information from multiple sources, must now face the task of maintaining orientation and overcoming illusions by determining which sensory channels are presenting correct information and ignoring information from sensory channels that are not.

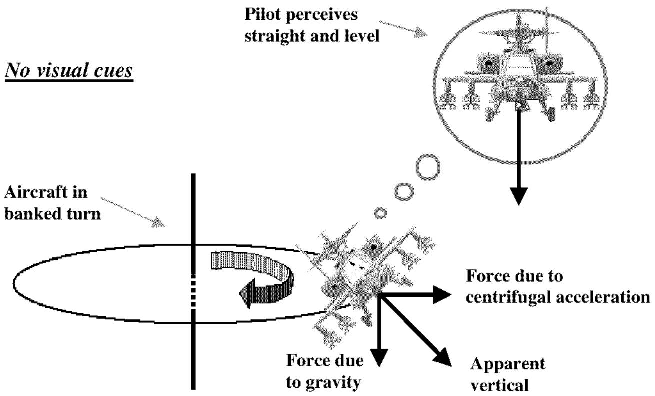


Figure 2: *Inaccurate perception of down (adapted from Benson, 1999b).*

Aviators are instructed to use a strategy of visual dominance, visual orientation cues are used to maintain spatial orientation to the exclusion of all other sensory cues, including vestibular and somatosensory (Gillingham and Previc, 1996). The pilot must learn to interpret the focal visual information on the attitude indicator and other flight instruments to develop a concept of where he is, what he is doing, and where he is going, and to refer to that concept when controlling his aircraft.

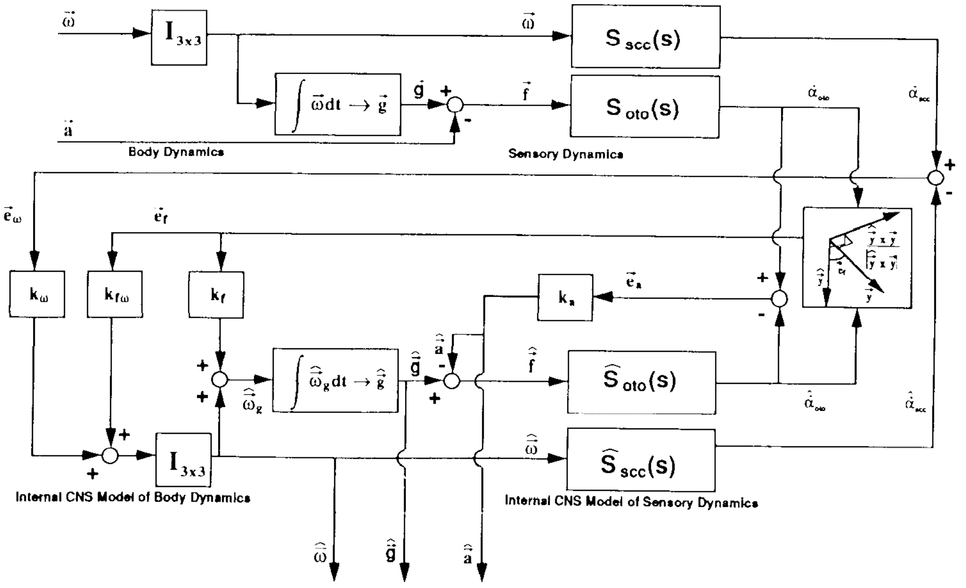
The typical SD mishap occurs when visual attention is directed away from the aircraft's orientation instruments and/or the horizon (due to, for example, temporary distraction, increased workload, cockpit emergencies, transitions between visual and meteorological conditions, reduced visibility, or boredom). Most SD mishaps are not due to radical maneuvers. When a pilot looks away from the horizon (loss of focal and peripheral visual cues), or looks away from his artificial horizon in instrument weather (loss of focal visual cues), the central nervous system computes spatial orientation with the remaining information at its disposal, vestibular and somatosensory. The vestibular and somatosensory information are concordant, but frequently incorrect. In such circumstances, it is physiologically normal to experience spatial disorientation. Furthermore, conflicts between focal visual and vestibular orientation information tend to resolve themselves in support of the vestibular information (Gillingham and Previc, 1996). This may lead the pilot to fail to make corrections to the aircraft's flight path, or to make inappropriate corrections, leading to an SD mishap.

Method

The Naval Aerospace Medical Research Laboratory (NAMRL) has developed an SD mishap analysis tool to support US Navy mishap boards in their investigations, to provide insight into the problem of SD in naval aviation, and to train aviators to avoid SD mishaps. The SD mishap analysis tool uses spatial orientation models and computer animation techniques to produce three-dimensional (3-D) computer simulations of SD mishaps.

Modelling of the spatial orientation system and predicting spatial orientation perception represent a classic bioengineering problem and there exists many examples in the vestibular sciences literature. Merfeld, Young, Oman and Shelhamer, (1993) reviewed the existing spatial orientation models and grouped them into two categories that are based on the underlying engineering formulation of the problem. The first is the "classical systems model" that uses classical control theory to model the components of the vestibular system. Information from these components is processed using regression analysis to estimate subjective orientation. Many authors have used this technique to describe components of the vestibular system, including Robinson (1977), Raphen, Matsuo, and Cohen (1977) for the semicircular canals and velocity storage mechanisms, and Grant and Best (1986) for the otolith organs. Mayne (1974) proposed a framework that explains how the information from the vestibular system is processed to give subjective orientation. This framework was the basis of a spatial orientation model implemented by Grissett (1993).

The second type of model is the "observer theory model" that uses optimal estimation theory to model spatial orientation first described by Oman (1980). Borah, Young, and Curry, (1988) and Pomelliot (1990) developed spatial orientation models based on this approach using Kalman filter techniques as the optimal estimator, and Merfeld *et al.* (1993) published a model based on observer theory that uses a constant gain estimator to predict spatial orientation (Figure 3). The SD mishap analysis tool uses both an observer theory model adapted from Merfeld *et al.* (1993), and a classical systems model adapted from Grissett (1993) to estimate spatial orientation perception.



The model outputs are estimates of angular velocity, gravity, and linear acceleration.

Figure 3: *Three-dimensional sensory conflict model (from Merfeld et al., 1993).*

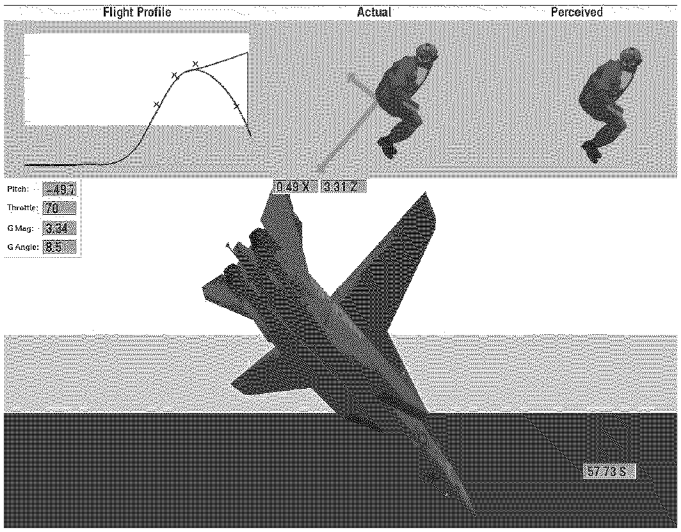
There are currently 4 steps in the NAMRL SD mishap analysis process to develop a 3-D mishap simulation:

Step 1: Using data from flight data recorders; eyewitness accounts; videotapes; and ground, ship, and aircraft radar transcripts, estimates of the 3-D angular position and velocity, and 3-D linear acceleration of the mishap aircraft are calculated using the mathematical analysis software package, MatLab™ (The MathWorks, Inc.)

Step 2: The estimates of the 3-D angular position, angular velocity, and linear acceleration of the mishap aircraft are input into the spatial orientation models to produce an estimate of perceived pilot orientation. The SD mishap analysis tool uses both an observer theory model, and a classical systems model to estimate spatial orientation perception using the modelling analysis software package Simulink™ (The MathWorks, Inc.). Both of these spatial orientation models do not include visual or somatosensory inputs, and are based on vestibular models from current literature and additional data from centrifuge, aircraft experiments, and aircraft mishaps gathered at NAMRL over the previous 40 years. The spatial orientation models assume that the pilot is not using outside visual horizon cues, and the pilot does not look at the aircraft instruments.

Step 3: To determine the accuracy and validity of the perceived pilot orientation, including analyses when the model results are significantly different, the perception results are evaluated using data from other sources, including pilot control inputs, expert advice on the mission, and eyewitness accounts. If required, the estimated perceptual results are modified to overcome the limitations of the spatial orientation models to produce a more accurate estimation of the perceived pilot orientation. For example, in Figure 6, the perceived pitch at approximately 45secs was modified to account for the sudden stick position change. At that time, it was concluded that the pilot became aware of the "true" pitch, and performed the rapid movement on the stick.

Step 4: The estimated perceived pilot orientation, along with computer models of the actual aircraft, flight data, and actual pilot position, are then used to develop a 3-D computer simulation of the SD mishap under consideration using a 3-D software simulation package, Vega™ (MultiGen-Paradigm, Inc). This simulation package provides an intuitive tool that permits visualization of a complex problem. Aircraft models and databases are created in Creator™ (MultiGen-Paradigm, Inc) and also imported into Vega. The Vega mishap simulation includes models of the actual aircraft and flight data, actual pilot position, and estimated <u>perceived</u> pilot position as shown in Figure 4.



Pitch: -49.7
Throttle: 70
G Mag: 3.34
G Angle: 8.5
0.49 X
3.31 Z
57.73 S

Figure 4: *Screen-shot of SD mishap tool 3-D computer simulation.*
Flight Profile is plot of altitude vs. ground track showing actual flight path (blue) and perceived path (red) based on predicted perception

These simulations provide an intuitive tool that permits visualization of a complex problem. Figure 5 shows a screen-shot from the analysis of an F-14 mishap from FY1996 to graphically illustrate the difference between the pilot's estimated perceived pitch (pitch up- calculated using the orientation models), and the actual pitch (pitch down – calculated from radar transcripts) that ultimately lead to an SD mishap.

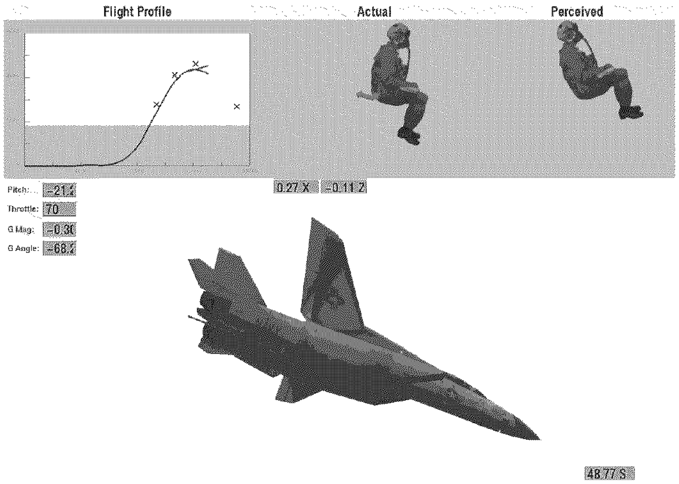


Figure 5: *Screen-shot of SD mishap tool showing difference between pilot perceived pitch and the actual pitch.*

Videos produced with the Vega simulation have been telecast on CNN, ABC News, and The Discovery Channel.

Results

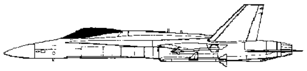
Table 1 shows the total mishaps for the US Navy for FY2001, and Table 2 shows the subset of these mishaps when the major causal factor was spatial disorientation. US Navy SD mishap statistics (26% of total mishaps, 50% of fatalities) for FY2001 are consistent with previous years and other services. SD mishaps remain a major problem in terms of lives lost (10) and aircraft (5). The analysis of an SD mishap from FY2001 that follows is provided to demonstrate the use of the SD mishap tool to support US Navy mishap boards in their investigations, and to provide insight into the problem of SD in Naval aviation.

Table 1: **US Navy Mishaps FY 2001**

F/A-18 Hornet	CRASHED DURING WTI TRAINING FLIGHT,	0
F/A-18 Hornet	NIGHT CATAPULT LAUNCH	**1 FATAL**
F/A-18 Hornet's	COLLIDED DURING NIGHT TRAINING EX.	0
S-3B Viking	CRASHED DURING DAY NATOPS CHECK FLIGHT	0
MV-22B Osprey	CRASHED DURING NIGHT TRAINING FLIGHT	**4 FATAL**
T-45A Goshawk	PORT MAINMOUNT EXTENDED DURING MACH RUN	0
TAV-8B Harrier	CRASHED ON DAY SHORT FINAL APPROACH	**2 FATAL**
T-45A Goshawk	CRASHED INTO WATER FROM DAY CQ PATTERN	**2 FATAL**
F/A-18 Hornet	SUFFERED MULTIPLE PELICAN STRIKES	0
F-14 Tomcat	LANDED GEAR-UP DURING NIGHT FCLP	0
T-34C TurboMentor	STRUCK WIRE DURING DAY LOW SAFE MISSION	**2 FATAL**
F/A-18 Hornet	CRASHED DURING DAY FERRY FLIGHT	**1 FATAL**
T-34C TurboMentor	CRASHED DURING DAY PROFICIENCY FLIGHT	**2 FATAL**
HH-46D SeaKnight-	CRASHED INTO WATER ON DAY TAKEOFF LHD	0
HH-1N	MADE HARD LANDING DURING CIVILIAN SAR MISSION	0
CH-46E SeaKnight	CRASHED INTO RIVER DURING DLQ ON NVG's	**3 FATAL**
F-14 Tomcat	FAILED TO RETURNFROM NIGHT MISSION	**2 FATAL**
F/A-18 Hornet	CRASHED DURING 2V2ACM TRAINING FLIGHT	**1 FATAL**
F/A-18 Hornet	RIGHT ENGINE FIRE ON TAKEOFF	0

Table 2: **US Navy SD Mishaps FY2001**

F/A-18 Hornet	NIGHT CATAPULT LAUNCH	**1 FATAL**
TAV-8B Harrier	CRASHED ON DAY SHORT FINAL APPROACH	**2 FATAL**
T-45A Goshawk	CRASHED INTO WATER FROM DAY CQ PATTERN	**2 FATAL**
CH-46E SeaKnight-	CRASHED INTO RIVER DURING DLQ ON NVG's	**3 FATAL**
F-14 Tomcat	FAILED TO RETURN FROM NIGHT MISSION	**2 FATAL**



F/A-18C HORNET
NIGHT CATAPULT LAUNCH

1 FATAL

Event Summary:

The Mishap Aircraft (MA) crashed into the water after night catapult launch. The Mishap Pilot (MP) was well rested and mentally prepared for the Mishap Flight (MF). MP spent significant time troubleshooting several discrepancies while on deck, all of which were satisfactorily resolved prior to MA launch. Weather conditions were overcast at 600-1000 ft, creating an extremely dark night under the low overcast. MP conducted a normal catapult shot with sufficient airspeed for flyaway. Almost immediately after launch, MP grabbed the stick and easily countered a slight roll to the right due to MA asymmetric condition. MP gradually applied forward stick during the climb out. After peaking in altitude at 224AGL, the MA responded to the forward stick by accelerating and following a nose down flight path toward the water. Just prior to water impact, MP realized he was in extremis and attempted to eject, but was already out of the ejection envelope resulting in an unsuccessful attempt. MP lost at sea.

Official Cause Factor:

AIRCREW: MP applied improper forward stick inputs during climb out due to the effects of somatogravic illusion.
WHO – Aircrew, Pilot at control, Pilot in command.
WHAT – Aircrew, Improper use of flight controls in the air, performed wrong action.
WHY – Physiological, mis-perception, vestibular illusion.

NAMRL Analysis:

Aircraft data from the flight data recorder that influences spatial orientation were analyzed and evaluated at NAMRL. There are several points of interest:

As you will note from the stick position plot (green stars, Figure 7) the pilot makes continuous small inputs/corrections until just prior to impact when he makes a large stick back input. This indicates he is conscious and aware throughout the 12 sec of flight (i.e., this was not a G-LOC mishap). It also strongly suggests that he became aware of his true attitude at the last instant before impact, when there was insufficient time for the aircraft to respond.

The plot of estimated perceived pitch (blue line with circles, Figure 7) is derived from the NAMRL perception model. It assumes that:

- On the night of the mishap it was a truly dark night and that there were no outside visual horizon cues.
- The pilot was not looking at the aircraft instruments.

This allows us to combine the resultant vector data of Figure 6 with the perceptual time constant decays from our model to produce the relatively constant perceived pitch up of 18 to 20 degrees from 4 sec after launch to just prior to impact. In a normal launch, the pitch up perception would decay more rapidly than indicated in this plot. However, the mishap aircraft is increasing in speed throughout the trajectory as the pilot pushes forward on the stick. This, in turn, increases the magnitude of the longitudinal acceleration vector and maintains the illusion of a pitch up perception. This is essentially a positive feedback situation for pitch perception. This false pitch perception can be classified as an example of the somatogravic illusion.

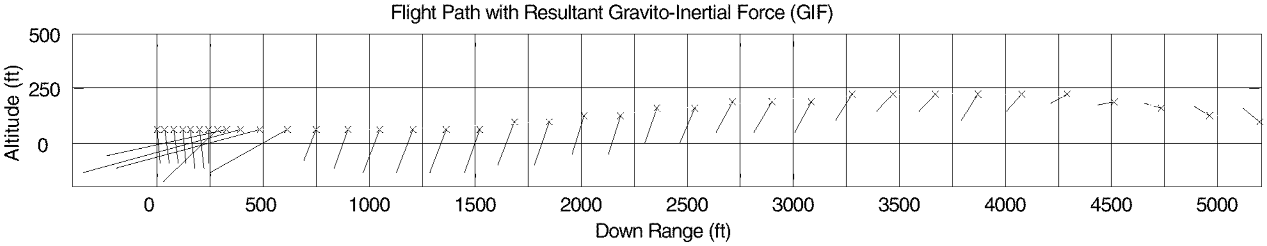


***Figure 6:** Flight path with resultant Gravito-Inertial force*

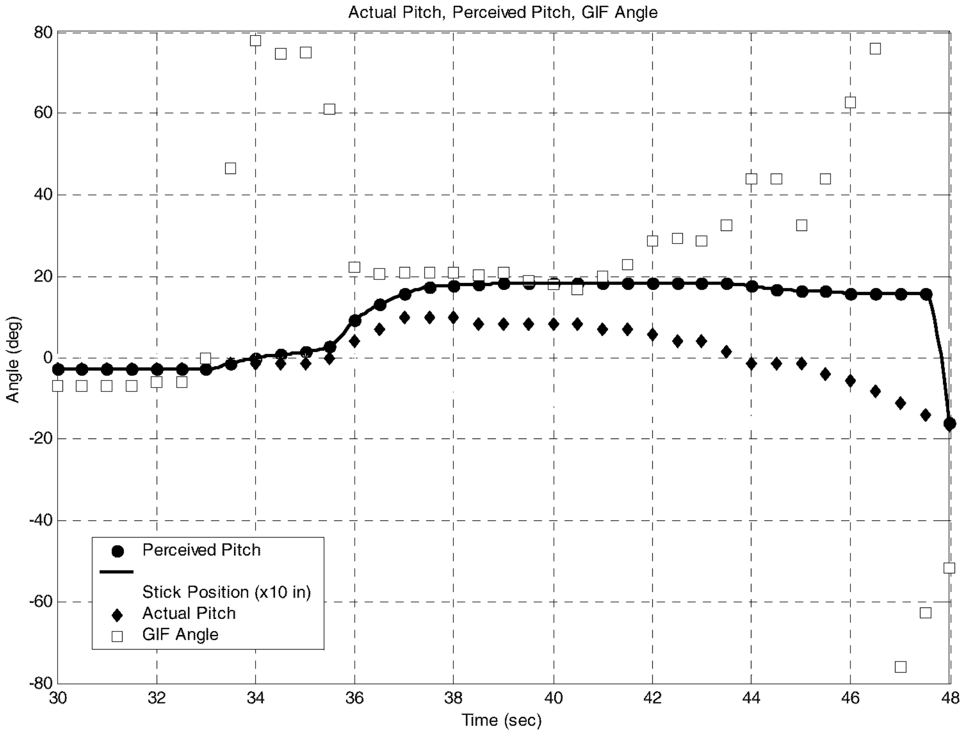
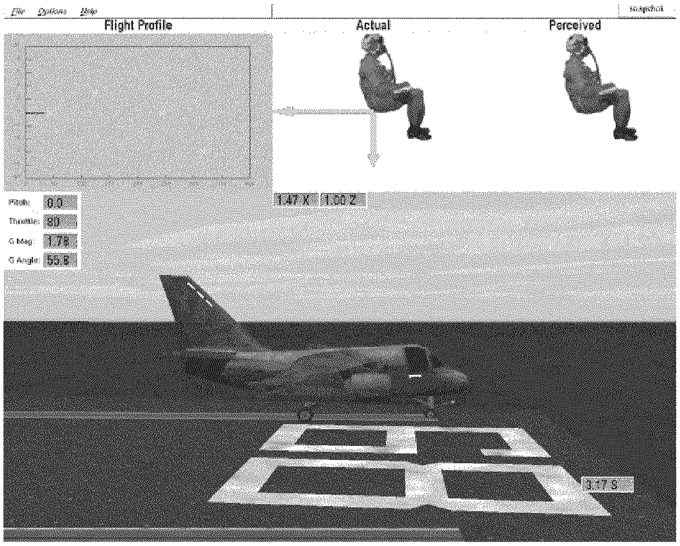


***Figure 7:** Actual pitch, perceived pitch, Gravito-Inertial force angle*

As in all somatogravic illusion mishaps, it has to be assumed that the pilot was not engaged in a proper instrument crosscheck. The most frequent explanation is that an element of DISTRACTION or complacency occurred. It is difficult to believe that complacency could occur under the high stress conditions of a catapult launch at night. There was a "rash" of these mishaps in the 1960's leading to the research that has produced some of the data required to create the perceptual model. This mishap is almost identical to an S-3 launch mishap in FY1996 (Figure 8). The flight profile and duration match almost perfectly. In both situations no communication calls were received. Unfortunately, this F/A-18 mishap is a classic textbook example of the somatogravic illusion on launch.



Pitch: 0.0
Throttle: 80
G Mag: 1.78
G Angle: 55.8
1.47 X
1.00 Z
1.17 S

Figure 8: *Screen-shot from S-3 catapult launch mishap simulation.*

Discussion

Spatial disorientation (SD) mishaps for military air forces, commercial aviation, and general aviation have an estimated annual cost in the billions of dollars. The NAMRL developed SD mishap analysis tool uses two models of spatial orientation perception that are based on current literature and data from centrifuge studies, aircraft experiments, and aircraft mishaps gathered at NAMRL over the previous 40 years. The spatial orientation models currently used in the SD mishap analysis tool are adequate to address many types of mishaps, including the somatogravic illusion mishap illustrated here. However, these models do not address all of the relevant operational factors encountered in US Navy flight operations (e.g., flying with NVGs and flights with large roll maneuvers). Therefore, the current SD mishap analysis tool does not provide an accurate description of a pilots' perception in <u>all</u> US Navy aviation environments.

To enhance the existing SD mishap analysis tool, further research and development is required to produce an improved spatial orientation model. An ideal model would be a complete system containing mathematical representations of all sensory inputs (vestibular, visual, audio, tactile, proprioceptive), and an advanced mathematical representation of the central nervous system. Other improvements to the mishap analysis tool include adding intelligent, knowledge-based software to quantify the risk and extent of disorientation, and advanced computer animation techniques to improve the realism of the simulation. Intelligent knowledge-based software enables a computer to make a decision that is normally made by a human with special expertise. Such a software approach should provide more accurate, repeatable predictions of disorientation.

To extend the operating envelope of the spatial orientation model to all aviation environments, a combination of additional in-flight testing and laboratory testing is required. However, existing laboratory testing devices have limited degrees of freedom, and cannot fully reproduce the current and future aviation acceleration environment. Therefore, new laboratory multi-degree of freedom centrifuge systems need to be developed that are capable of providing data to improve models of spatial orientation.

The F/A-18 mishap presented in this report is not a rare type of mishap. For the past several years, NAMRL has assisted on at least one case per year of somatogravic illusion in the “fast mover” communities (three such mishaps in FY2001). Somatogravic illusion mishaps are not always associated with catapult launches, but may also occur in high performance takeoffs, landings and bombing runs over land. When it is a high visibility mishap such as the FY1996 F-14 mishap, where there were flagrant violations, it is all too easy to blame the pilot and ignore that the final link in the mishap chain was spatial disorientation. However, when the pilot is one of the best pilots in the squadron performing a routine mission such as a FY1997 F/A-18 mishap, then it is more difficult to reconcile as a mere lack of attention. Even the most dedicated, highly professional pilots are not immune to experiencing somatogravic and other vestibular illusions. These are *normal* physiological responses experienced by all pilots when they are subjected to acceleration forces in the absence of corrective visual inputs.

In this type of mishap, virtually every mishap board finds the pilot at fault for not maintaining an adequate “cross check” of instruments. There are often extenuating circumstances, such as operational demands or high workload. However, the bottom line is that the pilot simply did not maintain a sufficient crosscheck of the instruments and permitted the “aviate” portion of “aviate, navigate and communicate” to go by the wayside. As discussed by Wolfgang Langewiesche (1943), this complex talent must be developed through extensive training and maintained through practice; and it is the fragility of this concept that makes SD such a hazard. We continue to lose fine pilots and aircraft every year. Given that non-material solutions (e.g., training and safety stand-downs) have not reduced the SD mishap rate below the current level, the largest portion of the blame may now rest with aircraft designers, in particular human factors engineers, who design instruments that provide information only when the operator devotes visual attention to that instrument. There are a variety of technologies that may have prevented the SD mishaps cited in this paper, and more importantly future similar mishaps. It is the responsibility of mishap boards to make appropriate recommendations to the parties that can provide the necessary resources to effect changes in aircraft and information management systems.

Conclusion

The NAMRL developed SD mishap analysis tool permits visualizing causal factors in SD mishaps so that mishap boards, JAG investigations, and congressional hearings can conduct thorough and accurate investigations and make appropriate recommendations. These efforts will reduce SD mishaps in aviation and other high performance platforms.

Recommendations

1. Enhance the SD mishap analysis tool by:
   a. Conducting further research and development to produce an improved spatial orientation model that overcomes limitations of existing spatial orientation models.
   b. Develop intelligent, knowledge-based software to quantify the risk and extent of disorientation.
   c. Develop advanced computer animation techniques to improve the realism of the simulation.

2. Extend the operating envelope of the spatial orientation model through a combination of in-flight testing and laboratory testing. Develop new laboratory multi-degree of freedom centrifuge systems capable of providing data to extend the spatial orientation model.

3. All existing and future spatial orientation models need to be validated and compared against each other using both mishap and laboratory data.

4. The SD mishap analysis tool must be developed to operate in real-time, to allow for the eventual use of the analysis tool for real-time prediction in high performance platforms.

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