THE USE OF HELMET-MOUNTED DISPLAY ATTITUDE SYMBOLOGY AND AUDITORY ATTITUDE INFORMATION FOR UNUSUAL ATTITUDE RECOVERIES

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This study investigated the effect of adding auditory attitude information to standard visual attitude symbology on pilot performance. Eight military pilots participated in 48 unusual attitude recovery tasks. Results showed that there was no significant difference in performance for the type of symbology presented (visual only, visual plus non-localized verbal commands, and visual plus localized audio tones) in terms of all of the dependent measures (time to initial correct control input, total recovery time, and absolute altitude change). However, questionnaire data showed that 7 of the 8 pilots preferred to perform the recoveries with some type of audio cueing in addition to the visual symbology.

Introduction

Spatial disorientation (SD) has been defined in many ways, but the widely accepted definition for the aviation community is a false percept of attitude, position, or motion relative to the plane of the earth's surface (Gillingham and Previc, 1996). SD accidents result in lost lives and aircraft, and continue to cost the Department of Defense over $300 million per year. "On average, the USAF 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, DeVilbiss, Yauch, and Brown, 2000, pp. 489). For the past three decades, the percentage of accidents attributed to SD has remained relatively constant. Traditional approaches to solving the SD problem have relied on training and policy guidance. With no apparent decline in the accident rate, researchers have been focusing their attention on visual display symbology development and testing, primarily because ninety percent (90%) of orientation information comes from one's visual system (Aircraft Operators and Pilots Association, Air Safety Foundation, 2001). However, due to the popularity of add-on systems, more complex cockpits, and tougher missions, pilots are spending more time away from their attitude instruments during flight. Therefore, the answer may not be in changing the visual attitude information, it may be in augmenting the visual information with additional attitude information presented in non-traditional ways that pilots can utilize when they are visually saturated with data that does not contain attitude information.

The approach in this study involves taking advantage of human sensory integration by providing orientation information via multiple sensory modalities to help combat the problem of pilot SD. This can help pilots in multiple ways. First, pilots can equate audio symbology with visual symbology when both are present, then continue to acquire attitude information via the audio channel when they remove their gaze from the visual attitude information. Second, it can provide an over-whelming amount of correct attitude information in the event that real-world visuals are compromised (flying at night or in clouds) so pilots will be able to overcome the strong (and sometimes erroneous) kinesthetic sensations that cause them to control the aircraft in an undesirable manner. For instance, if the attitude information being displayed visually is reinforced with supplemental attitude information via audio information indicating the direction of the horizon or the sky, this may provide adequate information for one to overcome the disorientation.

The use of audio information (localized and non-localized) for portraying aircraft attitude has not been recently investigated since the technology has matured to a state where it can be effective. However, the addition of localized audio to visual information has been shown to effectively redirect gaze (Perrott, Cisneros, McKinley, and D'Angelo, 1996), and significantly reduce the amount of target search and detection time as compared to visual-only times (visual only target identification time with 50 distractors was 15.8 seconds, visual plus audio target identification time with 50 distractors was 1.5 seconds) (Simpson, Bolia, McKinley, and Brungart, 2002). Also, 3-D audio is slated for incorporation in the Joint Strike Fighter (Scott, 2000). Thus, the usefulness of adding audio attitude information to visual attitude information was examined in this study.

Objective

The objective of this study was to determine the effects of the addition of auditory attitude information to visual helmet-mounted display (HMD) attitude symbology on pilot performance when recovering from unusual attitudes.

Method

Participants

Eight rated military pilots participated in this study. Subjects had a minimum of 100 hours of head-up display (HUD) experience. Their average flight time was 1652 hours in various fighter aircraft (F-4, F-14, F-15, F-16, F-18, and A-7).

Apparatus

Evaluation cockpit. A fixed-based, single-seat fighter cockpit simulator was used for this evaluation. It contained a side-mounted, limited-displacement F-16 transducer with an F-15E stick and grip, and F-15E throttles. The head-down displays were portrayed on a single 21" x 16" Matsushita color monitor partitioned into three 6 x 8 displays and an upfront control unit. A BARCO Retrographics 801 systems supported the out-the-window scene, providing a 37° horizontal by 27° vertical field of view.

HMD. A Kaiser Sim-Eye 40 HMD was used to present visual attitude symbology to the pilots. The HMD was binocular with 100% overlap, had a 40° circular field of view (FOV), and 1280 x 1024 resolution. The HMD was see-through so pilots could view the symbology and the out-the-window visual scene at the same time.

3-D Localized Audio System. A 3-D Audio Display Generation (ADG) System, which ran on a Virtual Control Panel software application, was used to generate and present the 3-D localized audio symbology. The software was hosted on a PC and allowed for the specification of position (azimuth and elevation) and volume of the audio input. The third dimension, range, remained fixed for this study. The ADG interfaced to the head tracker to receive head orientation information and modify the location of the sound so the location of it appeared stationary. A Bose active noise reduction headset was used with this system.

Head Tracker. An Ascension Flock-of Birds 6-D Multi-Receiver/Transmitter Tracking Device was attached to the pilot's helmet to measure pilot's head position coordinates and orientation angles. This information was sent to the HMD system and the 3-D audio system to ensure that the HMD symbology and the 3-D audio tones were properly correlated with the pilot's head position. For instance, the horizon symbol on the HMD remained conformal to the true horizon, regardless of head movements.

Software. All of the software for the simulation was running on a combination of Silicon Graphics and PC workstations. An F-16 aeromodel was used to fly the flight tasks. The head-down display suite contained a tactical pilotage chart, instruments, a crew-alerting system status display, and an up-front controller. The out-the-window scene graphics, which were used during familiarization flying only, consisted of a database of Utah. During data collection, the out-the-window scene graphics portrayed instrument meteorological conditions (IMC) and consisted of only a white background.

The HMD symbology was only presented when the pilot was looking on-boresight, and consisted of the Military Standard 1787 HUD attitude symbology (U.S. Department of Defense, 1996) shown in the traditional HUD FOV of 30° horizontal by 20° vertical. As the pilot looked off-boresight, the symbology disappeared. When HUD symbology is portrayed on the HMD with the same characteristics of the HUD, it is referred to as the "Virtual HUD".

Study Conditions

To determine the added value of audio symbology, non-localized verbal commands as well as localized audio tones (variable azimuth and elevation with fixed range) were tested. These were combined with visual symbology to create three levels of the attitude symbology set variable.

Visual Only. In the visual only condition, subjects used the HMD attitude symbology to recover from the unusual attitudes.

Visual Plus Non-Localized Verbal Commands. In this condition, subjects used the HMD attitude symbology and a series of non-localized verbal commands to recover. Because the commands were non-localized, pilots always heard the commands simultaneously in both ear cups, regardless of their head position. The non-localized verbal commands consisted of the phrases "roll left", "roll right, "pull up", and "pull".

The specific non-localized verbal commands played were based on the current attitude of the aircraft and correct recovery procedures based on Air Force Manual (AFM) 11-217 Instrument Flight Procedures (U.S. Department of Air Force, 1996). For instance, given initial conditions of +45° roll and –60° climb/dive angle, the correct recovery procedure was to roll to a wings level upright attitude, and correct to level flight. Therefore, the first non-localized command was "roll left" to achieve wings level. When the subject achieved an attitude to within ±5° of 0° roll, the "roll left" command ceased. Then the command "pull up" sounded until the aircraft was within ±5° of 0° climb/dive angle. In a nose high condition (+45° roll and +45° climb/dive angle), the correct recovery procedure was to roll past 90° to create a positive lift vector, pull the nose down, and then roll wings level at the horizon. For this initial condition, since the aircraft is in a +45 degree roll, the first command was "roll right" to increase the right bank from +45° to greater than +90°. Once the subject exceeded 90°, the command changed to "pull". As the aircraft neared the horizon (±5° of 0 climb/dive angle), the "roll left" command was sounded, instructing the subject to roll wings level.

Visual Plus 3-D Localized Audio Tones. In this condition, subjects used the HMD attitude symbology and a series of 3-D localized audio tones to recover. By using the head tracker data, the tones were perceived as emanating from a static location in the external environment, regardless of the pilot's head position. For instance, if a tone was representing something to the pilot's left, the tone would sound in the left ear cup only when the pilot looked straight ahead, but in both ear cups if the pilot turned his head directly to the left (the perceived origin of the tone).

The 3-D localized audio tones were presented based on the current attitude of the aircraft and the correct recovery procedures. The 3-D localized audio symbology consisted of a "fly-to" command to help pilots achieve straight and level flight. This symbology consisted of a tone presented at different locations based on the current attitude of the aircraft. The tone sounded either on the subject's left side at head level (azimuth at 270°; elevation at 90°; Figure 1), on the subject's right side at head level (azimuth at 90°; elevation at 90°), or in front of and above the subject (azimuth at 0°; elevation at 45°). The localized audio symbology was a complex signal to include the tone presented at 85 decibels (dB) with white noise in the background presented at 75 dB to assist in localization.

Using the same examples from the previous description, given initial conditions of +45° roll and

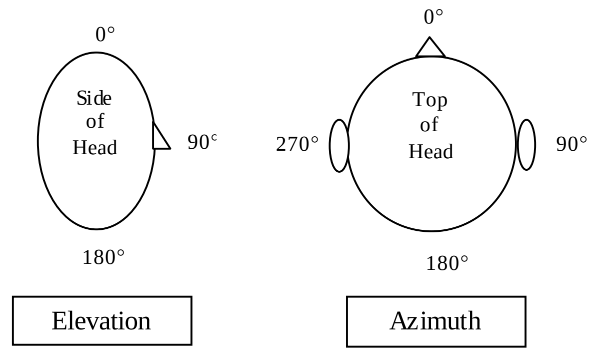

Figure 1. Azimuth and Elevation Position Definition.

–60° climb/dive angle, the correct recovery procedure was to roll to a wings level upright attitude, and correct to level flight. Therefore, the first 3-D localized cue was the tone with accompanying background noise presented to the left of the pilot in 3-D space (azimuth of 270°; elevation of 90°) to indicate that the pilot should roll left to achieve wings level. When the subject reached an attitude of within ±5° of 0° roll, the cue ceased. Then the tone with accompanying background noise sounded above the pilot to indicate that they needed to fly to the tone and thus pull up (azimuth of 0°; elevation of 45°) until the aircraft was within ±5° of 0° climb/dive angle. In a nose high condition (+45° roll and +45° climb/dive angle), the correct recovery procedures were to roll past 90° to create a positive lift vector, pull the nose down, and roll wings level at the horizon. For this initial condition, since the aircraft was in a +45° roll, the first cue was the tone with noise presented to the right of the pilot in 3-D space (azimuth of 90°; elevation of 90°) to indicate that the pilot should roll right to increase the right bank from +45° to greater than +90°. When the aircraft attitude exceeded 90°, the cue changed to a position above the aircraft (azimuth of 0°; elevation of 45°) to indicate to the pilot where to "pull" toward. As the aircraft neared the horizon (±5° of 0° climb/dive angle), the tone on the left sounded, instructing the subject to roll left to achieve wings level.

The second variable studied was unusual attitude initial climb/dive angle. Typically, total recovery times are significantly faster for nose low initial condition recoveries than nose high, and altitude lost (nose low initial conditions) is significantly greater than altitude gained (nose high initial conditions) (Reising, Barthelemy, and Hartsock, 1991). It was hypothesized that the addition of audio attitude information to the current visual attitude information would reduce these differences. Therefore, initial climb/dive angle was examined in this study.

Independent Variables

There were three levels of the first independent variable, attitude symbology set. These included visual only, visual plus non-localized verbal commands, and visual plus 3-D localized audio tones. The second independent variable was unusual attitude initial climb/dive angle. This variable had two levels – nose high initial climb/dive angle condition and nose low initial climb/dive angle condition.

Dependent Measures

The primary dependent variable for this task was time to initial correct control input. This was defined as the time from unusual attitude presentation to the first correct stick input. This measure is important because it helps identify the time it takes to recognize the aircraft attitude portrayed via the symbology (visual and audio) and how accurate that identification is. Other dependent measures included total recovery time (total task time minus time to initial correct control input), and absolute altitude change (altitude lost or altitude gained during the recovery).

Tasks

Pilots were asked to perform a number of unusual attitude recovery tasks in IMC. For each task, the cockpit displays, HMD, and out-the-window scene started out blank. When the subject depressed the start button, the displays (the out-the-window scene, the head-down displays, the HMD symbology, the non-localized verbal commands, and the 3-D localized audio tones, depending on the condition) were presented portraying the aircraft in a specific attitude. The subject's task was to recover to straight and level flight. A full recovery was specified in terms of attitude criteria maintained for a specific period of time, i.e., $\pm$5° climb/dive angle and $\pm$5° roll for 2.5 seconds. Participants were asked to use unusual attitude recovery procedures from AFM 11-217 Instrument Flight Procedures. There were eight unique unusual attitudes (Table 1) with two replications of each attitude for a total of 16 data collection tasks.

Experimental Design

This study employed a 3x2 full factorial within-subjects design. All eight subjects received all combinations of the three levels of the attitude symbology set and the two levels of the unusual attitude initial climb/dive angle condition. The presentation of attitude symbology set was counterbalanced across subjects. The presentation order of the 16 unusual attitudes was randomized for each subject.

Unusual Attitude	Climb/Dive Angle	Roll	Speed	Alt
1	+30	+75	353	11000
2	+30	-135	352	13000
3	-30	-45	401	12000
4	-30	+150	250	15000
5	+60	0	419	9000
6	+60	+120	459	13000
7	-60	+60	400	13000
8	-60	-135	378	13000

Table 1. Unusual Attitude Initial Conditions.

Procedure

Subjects were given a standardized briefing that included the purpose of the study and the schedule for the day. They were asked to sign a consent form and were given safety procedures. To determine subject's overall ability to localize the 3-D audio tones, a localization task was conducted. Subjects donned the audio headset with head tracker and were seated in the cockpit. A series of tones were presented to the subjects in various azimuth and elevation locations, and subjects were required to turn their head to "look" at the perceived location of the tone. The head tracker determined the location of the subject's head, and a comparison between the actual location of the tone and the position of the subject's head was made. This procedure was conducted to ascertain if subjects met a minimum criteria for localization capability.

Next, the head-down displays, the out-the-window scene, and the controllers were explained. The HMD attitude symbology was presented and discussed. Participants then performed familiarization flying, practice tasks, and data collection tasks. Familiarization flying consisted of a free-flight segment in which the pilot's main goal was to become familiar with the handling characteristics of the aeromodel while flying the out-the-window visual scene and viewing the HMD symbology. Following this segment of training, subjects performed practice unusual attitude recovery tasks in which the conditions they practiced (HMD symbology, non-localized verbal commands, and 3-D localized audio tones) were identical to the subsequent data collection session. Practice tasks consisted of four tasks with different unusual attitude initial conditions than data collection unusual attitudes, each repeated twice. Next, the 16 data collection unusual attitudes were randomly presented to the subject for that specific condition. After data collection under the first condition was completed, practice with the second condition began. This procedure of alternating practice tasks and data collection tasks continued until all data points were collected. After the final data collection segment, a questionnaire was administered.

Results

Based on the localization test procedure results, all eight subject's data were included in the subsequent analyses. A multivariate analysis was conducted and the omnibus F test showed no significant effect for attitude symbology set ($F(6,2) = 0.145$, $p = 0.972$). The results did show a significant main effect for unusual attitude initial climb/dive angle condition ($F(3,5) = 76.482$, $p = 0.0001$); but the interaction between the two independent variables was not significant ($F(6,2) = 0.777$, $p = 0.657$). Further analysis into the main effect for unusual attitude initial climb/dive angle condition revealed that the two levels of this variable differed in terms of total recovery time ($F(1,7) = 25.069$, $p = 0.0001$) and absolute altitude change ($F(1,7) = 195.758$, $p = 0.0001$). Figure 2 shows that pilots had better performance when the unusual attitude initial climb/dive angle condition was nose low in terms of total recovery time. Figure 3 shows that pilots performed better when the initial climb/dive angle condition was nose high in terms of absolute altitude change.

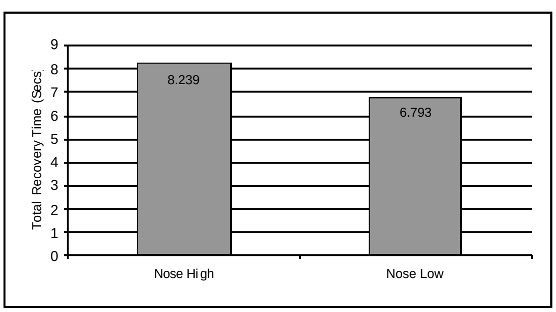

Figure 2. Means for Initial Climb/Dive Angle Condition in Terms of Total Recovery Time.

Discussion

The results showed that there was no significant difference between the three attitude symbology sets.

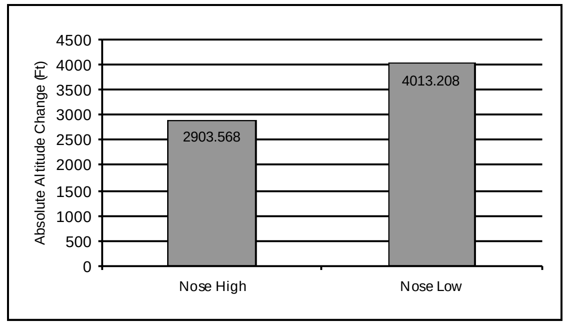

Figure 3. Means for Initial Climb/Dive Angle Condition in Terms of Absolute Altitude Change.

Averages for time to initial correct control input are plotted in Figure 4.

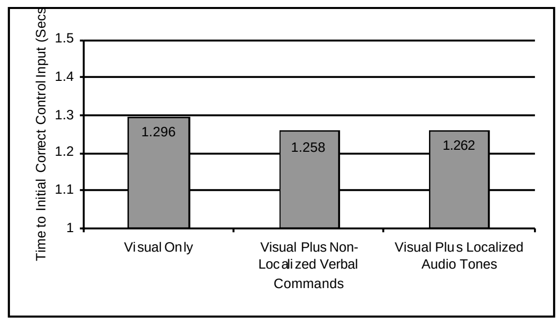

Figure 4. Means for Attitude Symbology Set.

Although there was no significant difference in attitude symbology set performance based on the objective data, questionnaire data showed that 7 of the 8 subjects preferred some form of auditory cueing in addition to the visual information for recovering from unusual attitudes. Five pilots preferred the non-localized verbal commands and 2 subjects preferred the localized audio tones. The reason most often cited during the debriefing for this difference in preference was based on the fact that, just as with the visual symbology, when pilots were presented with the visual and 3-D localized audio tones, the localized audio tones required some amount of interpretation time before responding. For example, once the visual and 3-D localized audio tones were presented, subjects had to determine the tone's location, remember that it was a "fly-to" command, and then initiate the control input. In contrast, once pilots were assured during practice that the non-localized verbal commands would always provide correct recovery information, they immediately followed the verbal command to initiate the recovery, and then confirmed the correct recovery procedure with the visual information after it was interpreted.

So why then, was this perceived difference in initial response time recounted by the pilots not evident in the objective performance data? First, there was a low number of subjects and high variability in the data. Second, experience with the visual symbology may have had some effect on the outcome of this study. Because the subject-pilots had many hours of experience with the HUD symbology (a minimum of 100 hours with an average of 1652), and limited training on the audio symbology, a performance difference among the three symbology was not found. Since general aviation pilots do not use HUDs and therefore should mot be familiar with standard HUD symbology, a future study will investigate the performance of general aviation pilots with audio and visual attitude information. This will ensure that the visual and audio symbology will receive equal training time. Finally, being the first of many studies investigating the use of audio attitude information coupled with visual attitude information, the audio symbology may not have been optimized for this task. Further research needs to be conducted in the area of tone selection. A "fly-to" command was thought to be most intuitive and equivalent to the non-localized verbal commands used for this study, but alternative localized audio commands need to be applied and tested.

In terms of the other independent variable (initial climb/dive angle), the significant main effect showed that the nose low recoveries had faster recovery times than the nose high initial conditions. This was expected because when the aircraft is in a nose low condition and diving, it is changing (losing) altitude much more quickly than when in a nose high condition. Also, the nose low conditions had significantly higher absolute altitude change. In the nose low condition, pilots were aggressively performing the recovery procedures because of the extreme consequences of a nose low condition (hitting the ground) as opposed to being in a nose high condition where the recovery procedures allow for a less aggressive recovery. Given that these results are consistent with prior research and the fact that the interaction between the two independent variables for this study was not significant, the value of this set of results is marginal.

Conclusions

Although there was not a significant difference in performance between the three attitude symbology sets, pilots preferred the addition of audio attitude information to the visual attitude symbology to help them recover from unusual attitudes. Further research should focus on determining the optimal audio symbology for portraying attitude information and integrating this with current visual attitude information.

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