ABSTRACT

One purpose of head-up displays in modern fighter aircraft is to provide the pilot with attitude information while allowing him to focus his attention outside the cockpit. However, current attitude symbology is deficient in its ability to answer important pilot questions about unusual attitude recovery. This study evaluated several advanced symbology concepts designed to resolve these deficiencies. The results indicate that the inclusion of multicolor coding and a fixed point of rotation for the dynamic pitch ladder symbology results in better unusual attitude recovery.

INTRODUCTION

The function of head-up displays (HUDs) has changed dramatically since their introduction into modern fighter cockpits. Designed to provide the pilot with virtual image symbology while allowing him to maintain visual contact with the external world, HUDs were originally implemented as dynamic bomb sights. Since they have evolved into highly complex displays presenting vast amounts of flight critical information, one such example of essential information is aircraft attitude. Pilots have always maintained an awareness of their aircraft's attitude from a number of sources. These sources have included the external visual world, a knowledge of previous aircraft attitude and subsequent flight control actions, trend data from internal cockpit displays (altitude, airspeed, angle-of-attack, etc.), and when any or all of these cuing sources became degraded or completely failed, the dedicated attitude director indicator (ADI). Although the ADI provides cues to sky/ground distinction, the extent of the attitude attained, and an easy reference for attitude recovery, it is hampered by two limitations inherent in its design. First, unlike the HUD, it requires pilots to transition their visual focus into the cockpit to interpret the information. Secondly, at night or in degraded weather conditions, when the possibility of an insidious onset of an unusual attitude is extremely high, pilots must first recognize that they are in an unusual attitude before they will refer to the ADI for attitude information.

HUD technology is an excellent display medium with the potential to overcome both of these limitations. However, current HUD attitude symbology is deficient in its ability to quickly and effectively answer the three key questions asked by pilots in order to recover from an unusual attitude: 1) Am I going up or down? 2) Am I inverted? 3) Where is the horizon?

Research conducted at the Royal Air Force's Institute of Aviation Medicine (Taylor, 1984) indicated that a key factor in overcoming these deficiencies in HUD symbology is 1) to implement global characteristics which create an easily recognized overall picture and 2) to include an integral stimulus dimension to produce redundancy gain performance improvements. An integral dimension (e.g., redundant color coding) does not require additional information processing by the pilot.

In order to evaluate Taylor's concepts, Zenyuh, Reising, McClain, Barbato, and Hartsock (1987) compared standard pitch ladder symbology (straight, parallel line segments) to a new angled pitch ladder design. This new angled design incorporated attitude rungs which were broken in the middle and were bent from the horizon at an angle corresponding to one-half their degree of deviation. This provided a global picture of the extent of deviation from the horizon and formed an arrow directing the pilots' recovery. Further global quality was created by only displaying the numbers on one side of the ladder (this allowed quick reference for wings level or inverted flight). Multicolor coding was
also added to the symbology providing the redundant integral stimulus as advocated by Taylor. In contrast to the monochrome (green) standard HUD symbology, the advanced design displayed a cyan sky, green ground and white horizon to provide a more distinct sky/ground separation.

THE PRESENT STUDY

The results of the Zenyuh et al. (1987) study showed poorer performance on the multicolor formats at attitudes where the aircraft nose deviated more than 30 degrees from the horizon. One possible explanation for this was that since green was used for the entire monochrome HUD and only for ground color coding in the multi-color HUD, confusion in interpreting the meaning of green may have resulted. Therefore, the ground symbology in the current study was color coded brown to avoid a recurrence of the problem.

The previous study also showed consistently better recovery performance when subjects had the horizon symbology present on the screen. From this result, and pilot discussions, it would appear that pilots recognize and recover from unusual attitudes more proficiently if a horizon indicator is always present, regardless of the aircraft’s attitude. The current study examined two possible methods of indicating the horizon in attitudes which exceed that level for which the actual horizon is displayed -- 1) include a wider, thicker pitch bar, and 2) show an artificial horizon caged to the outer edge of the display surface.

A final issue examined in the present study was where the point of rotation for the symbology should be located. Current HUD symbology, in most cases, is anchored to the dynamic flight path marker (FPM) causing the pitch ladder to “float” to the edge of the HUD; the symbology can become intermixed with other important information (i.e., airspeed, altitude, and heading scales), making unusual attitude recovery much more difficult. The current study implemented the symbology in both the fixed condition, where the FPM could move in the vertical direction only, and in the dynamic condition where the FPM could move both horizontally and vertically.

PURPOSE

This experiment was designed to examine the effectiveness of different versions of HUD symbology on the pilot’s ability to interpret aircraft unusual attitudes and execute recovery procedures.

METHOD

Subjects

Sixteen HUD experienced pilots participated in this study. The participants were from the US Air Force, US Air Force Reserve, Air National Guard, and other organizations at Wright-Patterson AFB.

Apparatus

Dynamic Cockpit

This study utilized a generic, advanced fighter concepts cockpit, roughly comparable in size to the F-15. The cockpit contained five cathode ray tubes (CRTs), but only one CRT was used in the experiment to present to the pilot each of the HUD formats.

HUD Formats

Eight different angled-bar HUD combinations were examined to determine their efficiency in conveying aircraft attitude information to the pilot. There were two versions each of three different HUD symbologies used in this experiment [COLOR (monochrome vs. multicolor), FPM MOVEMENT (free floating vs. fixed about the center of the HUD), and ARTIFICIAL HORIZON INDICATOR (wide pitch bar vs. caged horizon)].

The first horizon indicator consisted of a pitch line nearest the horizon that was thicker and wider than the other depicted pitch lines and was displayed only when the true horizon was not present. This format is referred to as the wide pitch bar. In the multicolor format, the wider bar was always in the opposite color of the other displayed pitch bars. The second format consisted of a caged horizon indicator represented by a dashed horizon line and one pitch bar (standard size and opposite of the other depicted pitch bars) on the same side of the horizon indicator as the true horizon. This format is referred to as the caged horizon. In the multicolor formats, the horizon indicator was white and the associated pitch bar was the opposite color of the other displayed pitch bars.

The two levels of color consisted of monochrome and multicolor formats. Four of the HUD formats were multicolor with solid cyan pitch bars for the sky, dashed brown pitch bars for the ground, and a white horizon line and velocity vector. Heading, airspeed, and altitude were presented in green. The four monochrome HUD formats presented all symbology in green.
The FPM could maintain two positions. First, it could be free to move both vertically and horizontally on the HUD during the unusual attitude, and secondly, it could be fixed about the center of the HUD, where it could only move vertically.

The angled-bar HUD was used in all the unusual attitude format evaluations. The angled-bar HUD consists of pitch bars bent like chevrons pointing in the direction of the true horizon, forming a channel for the pilot to follow in recovering to a horizon-level attitude. The inclination of the pitch bars equaled one-half of the pitch angle, increasing from horizontal at 0 pitch to a 45 degree inclination at 90 degrees of pitch. The formats were only presented in attitudes that were greater or equal to 45 degree pitch and roll relative to the horizon for both inverted and noninverted flight. The HUD also had a single column of pitch scale numbers on the right side of the pitch bars which rotated with the pitch bars; for example, if the pilot were in an inverted position, the pitch scale numbers would appear upside down on the opposite side of the pitch scale.

Every HUD displayed specific constants that supplied the pilot with important information. For instance, all HUDs had a horizon line that was wider and longer than the pitch bars. Also, the heading was contained in a rectangle located at the center top of the HUD. Digital formats for airspeed and altitude were displayed in rectangles on the left and right side of the HUD respectively.

Procedure

Subject Briefing

A standardized briefing was given to each pilot to familiarize him with the experimental cockpit. Specifically, the briefing included: 1) the purpose of the study, 2) information on the unusual attitude display formats, 3) experimental procedures, and 4) flight control training and operation.

Training and Data Missions

Each test session lasted approximately ninety minutes and was composed of eight five-minute free flights and eight data missions in which each data mission included eight unusual attitudes. The five-minute free flight preceded each data mission to familiarize the pilot with the handling characteristics of the cockpit system and the HUD symbology for the upcoming mission. The pilot was required to perform a pursuit tracking task on the HUD at the beginning of each data mission. An unusual attitude was randomly presented by the computer ten to fifteen seconds after the tracking task had begun. Recording of data began with the presentation of the unusual attitude on the HUD. The pilot was required to recover as quickly as possible, maintaining straight and level flight (i.e., + or - 2 degrees pitch and + or - 4 degrees roll) for a period of one second. If recovery was not completed within 30 seconds, the display would freeze, ending the event. If the pilot crashed the aero model during data recording, the task was aborted and repeated at the end of the remaining eight unusual attitudes.

Upon completion of the eight unusual attitudes for each HUD format, a questionnaire was administered to each pilot, asking him to evaluate that particular HUD. At the end of the entire test session, an overall evaluation was administered.

Performance Measures

Each of the subject’s performance was evaluated by measurement of the following dependent variables:

a. Total event time - The time from the aircraft’s entering the unusual attitude until recovery was completed and maintained for one second.

b. Completion Status - Whether or not the pilot was able to recover in the allotted 30 seconds.

Data Analysis

The data was analyzed using a Multivariate Analysis of Variance (MANOVA) Statistical Package for the Social Sciences (SPSS - MANOVA) program (Nie, Hull, Jenkins, Steinbrenner, and Bent, 1975).

RESULTS

The results of the data analysis showed no significant interaction effects. The main effect for FPM location was statistically significant ($F(2, 14) = 8.09, p < 0.01$). The FPM results are shown in Figure 1. The pilots took significantly less time to recover from an unusual attitude when using the fixed FPM. There was also a marginally significant effect for color ($F(2,14) = 3.21, p < 0.07$). [The reason the color results are reported is that multivariate analyses tend to be more conservative than their univariate counterparts. The univariate analysis showed that the percentage of successful attitude recoveries was significant at the $p < 0.025$ level]. The color results are
shown in Figure 2. The pilots had more successful unusual attitude recoveries when using the color HUD.

**DISCUSSION**

Two key factors account for the significance of FPM: the dynamics of the symbology creating greater search times and symbol clutter at the edges of the screen resulting in additional information processing. When the FPM was allowed to move laterally about the screen, the pilot had to locate the center of motion before determining his attitude. The additional dimension of motion also made it more difficult for the pilot to locate the direction of the horizon, a key task in unusual attitude recovery. These problems did not occur in the case of the fixed FPM because it was always located in the center of the screen.

The second factor, added information processing, occurred because the moving FPM forced the pitch ladder symbology to be displayed over the airspeed and altitude scales. In order to determine the attitude, the pilot had to cognitively declutter the FPM symbology from the scale symbology. This cognitive decluttering time, coupled with the added search time required to locate the FPM, resulted in significantly longer recovery times using the moveable FPM.

Color did not affect recovery times, but rather had an impact on the percentage of successful recoveries. Color provided an essential element in answering two other of the key questions in unusual attitude recovery -- 1) "Am I going up or down?", and 2) "Am I inverted?"

The cyan pitch lines (sky) told the pilot immediately that he was above the horizon; conversely, the brown lines (ground) told him he was below the horizon. The transition from cyan to brown, or vice versa, told him that he was going up or down. Also, if the brown lines were on the top of his display and the cyan lines were on the bottom, the color coding told him that he was inverted. The color, therefore, enabled the pilot to comprehend the unusual attitude situation faster than with only monochrome symbology. The result was more successful recoveries within the 30 second allotted recovery time.

While one version of the caged horizon was not superior to the other, the pilots reported that the concept of the horizon never disappearing from the display was an excellent aid to attitude recovery; it provided an immediate answer to the third key question in unusual attitude recovery -- "Where is the Horizon?"

The two studies reported in this paper have pointed the way to HUD symbology changes which could significantly aid the pilot in unusual attitude recoveries. These changes have been incorporated into the symbology shown in Figure 3. The next step is the flight testing of the best symbology from the simulation. Flight testing is currently scheduled to begin next year.

**REFERENCES**


Figure 1. Recovery Time Plotted as a Function of PBM Location

Figure 2. Percent Recoveries Completed as a Function of HUD Type

Figure 3. Advanced Head-Up Display Format