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PRIMARY FLIGHT DISPLAYS IN THE T-38C: WHEN DO DIFFERENCES AMONG DISPLAYS BECOME INCONSISTENCIES?

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In the 1980s the US military settled on counterpointers, or dials, as the standard gauge for display of airspeed and altitude in a head-up display (HUD). This format is now making its way into production aircraft, one of which is the T-38C, a US Air Force (USAF) fighter jet trainer. The T-38C is unique in possessing three primary flight displays: a head-down primary flight display (PFD) suite, a HUD in Military Standard (MIL-STD) emulation mode, and the same HUD in F-16 emulation mode. Differences among these displays include color, scale, and gauge format (e.g., tapes vs. dials). A study was conducted as part of the Air Force's primary flight display endorsement process to determine if differences among these displays represent inconsistencies that might have practical impact on pilot performance, situation awareness, or workload. Sixteen T-38 pilots flew maneuvers designed to test spatial orientation and trend perception. Maneuvers were flown with each PFD alone and in two transition conditions: from the MIL-STD HUD to the HDD, and from the F-16 HUD to the HDD. Flight performance data were collected and pilots also rated situation awareness (SA) and workload. Three senior USAF Instructor Pilots (IPs) graded each maneuver. No practically significant differences were found in performance: differences among conditions were small and not operationally relevant. Pilots actually rated SA higher and workload lower when using the F-16 HUD, even though HUD and HDD gauge formats differed when using this display. Pilots also rated the F-16 HUD higher than the MIL-STD for facilitating an efficient crosscheck, not presenting conflicting cues, and using an intuitive data manipulation scheme. The results support a conclusion that consistency within a PFD is more important than consistency across head-up and head-down PFDs: differences in location, color, and display medium may facilitate perceptual and attentional separation of the information displayed.

Introduction

The US military is now in its third generation of a Military Standard for primary flight symbology for HUDs (U.S. Department of Defense, 2000). A great deal of work has been done in generating this standard format (see Weinstein, Gillingham, & Ercoline, 1994) and this symbology set is now finding its way into production fighter/attack aircraft, including (with some modifications) the F-22, the T-38C, and the F-35. Entering the last decade of the 20th Century, the 1950s-era cockpit layout and flight instruments of the USAF T-38A and T-38B fleets had fallen well behind the pace of technological change when compared to the integrated avionics suites found in modern fighter and bomber aircraft, as well as the new T-6A primary flight trainer. Avionics-related skills required in bomber-fighter (BF) aircraft were not being taught or introduced in the T-38, and only one third of needed avionics-related skills and knowledge transferred from the T-38 to follow-on training. Follow-on BF training flight hours needed for weapons-system-specific training were instead being used to train fundamental avionics skills.

The basic flight characteristics and performance qualities of the T-38 remain well-suited for the BF Track and Introduction to Fighter Fundamentals (IFF) training missions. The T-38 Avionics Upgrade Program (AUP) incorporates all-new digital avionics and electronic cockpit displays into a proven training airframe and engine combination. The AUP package, which changes the aircraft designation to T-38C, includes a head-up display and up-front controls, electronic head-down multi-function display (HDD), hands on throttle and stick (HOTAS) controls, electronic engine displays, mission display computer, data transfer system, radar altimeter, and all new navigation and communications systems. The T-38C AUP results in improvements to training viability and capability and improved reliability.

The next generation of USAF fighter and bomber pilots will learn to fly HUDs in this unique trainer. One of the things that makes this aircraft unique is that the cockpit (Figure 1) includes three PFDs. The first PFD (Figure 2) is a full-color set of instrumentation presented on one HDD. Airspeed is presented on a single-turn dial with a logarithmic scale, attitude is presented via a standard ADI (Attitude-Director Indicator) ball, altitude is presented on a multi-turn dial with equidistant scale markings and digital readout, and vertical velocity is presented as a green arc with associated tic marks on the altimeter. The second PFD (Figure 3) is a monochrome HUD

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Figure 1. Cockpit of the T-38C.

Figure 2. T-38C head-down PFD.

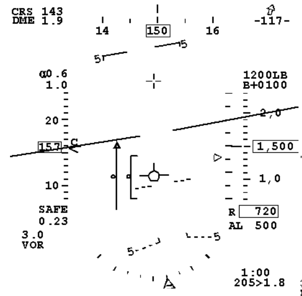

Figure 3. T-38C HUD, F-16 emulation mode.

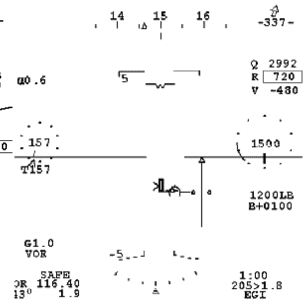

Figure 4. T-38C HUD, MIL-STD emulation mode

placed in F-16 emulation mode. Airspeed and altitude are presented on moving tapes, attitude is presented as a standard pitch ladder, and analog vertical velocity is presented as a fixed tape next to the altimeter with a moving triangle pointer. The final PFD is the same HUD placed in MIL-STD emulation mode (Figure 4). Airspeed and altitude are presented as multi-turn counterpointers with linear and equidistant scales, while analog vertical velocity is presented as an arc that grows clockwise (climb) or counterclockwise (descent) from the 9 o'clock position on the altitude counterpointer.

Until the advent of the MIL-STD HUD, USAF fighter/attack aircraft did not use head-up counterpointer symbology to present airspeed and altitude. Nor was the arc in Figure 4 used as a vertical velocity indicator. USAF fighter/attack aircraft HUDs have historically presented airspeed, altitude, and vertical velocity either digitally or via vertical scales (a.k.a., tapes). Why then, with all the training that USAF pilots had with tapes, would the Air Force switch to any other symbology?

As Weintraub and Ensing (1992) point out, there is an inherent ambiguity in the population stereotype for movement of an airspeed tape: it is unclear whether upward movement of the tape against a fixed pointer should represent an airspeed increase or decrease. To put it in "pilot speak", do the big numbers go at the top or the bottom? In the F-16 HUD (Figure 3), the big numbers go at the top and the scale moves downward as airspeed increases. In an A-10 HUD, the big numbers go at the bottom and the scale moves upward as airspeed increases. Counterpointers remove this ambiguity: clockwise movement always indicates an increase. Further, research conducted during the formation of the current MIL-STD HUD symbology looked specifically at the question of tapes vs. counterpointers and various presentations of vertical velocity information, including the arc on the counterpointer altimeter found in Figure 4. Three key studies in this area were Ercoline & Gillingham (1990), Hughes, Dudley, & Lovering (1990), and Weinstein, Ercoline, Evans, & Bitton (1992). A total of 56 experienced Air Force pilots flew various head-up display formats in fixed-base F-16 simulators throughout these studies and a strong preference for counterpointers was found. Performance was also found to be better with counterpointers during instrument maneuvering in turbulence.

Given the above, but also given the number of F-16s and F-16 pilots throughout the Air Force, it is understandable that those responsible for designing the T-38C would wish to include both formats. However, the same MIL-STD that contains a standard HUD symbology also dictates:

> "When multiple PFR displays are provided, the different displays shall conform to common display formatting, mechanization, and symbology conventions, except where doing so would unnecessarily constrain or degrade the functionality or quality of the displayed information. The formatting and mechanization conventions used on multiple PFR displays shall facilitate an efficient crosscheck across the displays, shall not present conflicting cues regarding flight parameters, trends, rates of change or display scalings, and shall utilize an intuitive data manipulation scheme."

The purpose of the current study was to examine the three proposed PFDs in the T-38C and determine if differences between these displays represent conflicting cues or inconsistencies that might interfere with an efficient instrument crosscheck. Sixteen USAF pilots representative of the T-38C target user population (i.e., no previous HUD experience) performed unusual attitude recoveries (UARs) and instrument maneuvers in simulated instrument conditions and were forced to transition between head-up and head-down PFDs during these tasks. Performance, situation awareness, and workload were measured and pilots rated the displays concerning how much they facilitated an efficient crosscheck, presented conflicting cues, and used an intuitive data manipulation scheme.

Method

Participants and Raters. Participants were sixteen male USAF pilots. None had previous experience with HUDs. Participant experience ranged from 250 to 1900 hours total flight time with an average of 630 hours. Average flight time in the T-38 was 355 hours. Three male USAF instructor pilots (IPs) rated each maneuver performed by participants in accordance with established USAF checkride criteria. The raters were all qualified and current USAF IPs averaging 3200 hours total flight time with an average 1320 hours in the T-38.

Apparatus. The simulator used for the study was a T-38C Operational Flight Trainer (OFT) used for training student pilots. The OFT consists of a cockpit identical to that in Figure 1, on a fixed base, and surrounded by projection screens to provide a 180° field of view. Because of limitations of the simulator, data were all collected by hand using stopwatches for start/stop times. All sessions were videotaped for later reference.

Experimental Design. The experiment was conducted using a 5 x 2 within-subjects design. The first independent variable was the PFD(s) used to perform the maneuver: HDD, F-16 HUD, MIL-STD HUD, Transition from F-16 HUD to HDD, and Transition from MIL-STD HUD to HDD. The second independent variable was type of maneuver performed: Unusual Attitude Recovery and Vertical S. Nested within UAR was the unusual attitude from which the recovery started, with four conditions: pitch +30˚, bank 135˚ left, airspeed 300 KCAS, altitude 13000 MSL; pitch -30˚, bank 150˚ right, airspeed 250 KCAS, altitude 15000 MSL; pitch +60˚, bank 120˚ right, airspeed 270 KCAS, altitude 13000 MSL; and pitch -60˚, bank 145˚ left, airspeed 400 KCAS, altitude 13000 MSL. Nested within Vertical S was the type of Vertical S: Vertical S-A with acceleration/deceleration, and Vertical S-D. Order of presentation within each maneuver type was randomized. Average IP rating (1 = Unsatisfactory, 2 = Fair, 3 = Good, 4 = Excellent), situation awareness rating, and workload rating were common throughout the experiment.

The results were analyzed separately by type of maneuver because most dependent variables were unique to each maneuver. The unique dependent variables for UAR were UA recognition time, UA recovery time, whether or not the first control input was correct, whether or not the UAR was performed correctly, the number of roll reversals during the UAR, and the altitude MSL at which the UAR ended. The unique dependent variables for Vertical S were the maximum deviations-from commanded airspeed, altitude, heading, vertical velocity, and bank; and the airspeed deviations at the top and bottom of the Vertical S.

Procedure. Participants were briefed on the conduct and purpose of the study, signed an informed consent form, and then familiarized with the three symbol sets by one of the IPs in the T-38C OFT. Participants then performed ten UARs, ten Vertical Ss, and ten UARs. In the UAR transition conditions, pilots initiated recovery using the HUD and continued recovery one second later using the HDD after failure of the HUD. Pilots were not informed in advance which trials were transition trials. In the Vertical S transition conditions, pilots were forced to transition from head-up to head-down and vice-versa every ten seconds by failures of the appropriate display. Following each maneuver, they rated situation awareness using the China Lake SA Rating Scale (Gawron, 2000) and workload using the Air Force Flight Test Center Workload Estimate Scale (Ames & George, 1993). Upon completion of all maneuvers (roughly 1.5 hours), participants completed a subjective questionnaire. All maneuvers were performed with the simulator out-the-window scene rendered a uniform gray to simulate instrument meteorological conditions. The simulation did not include turbulence.

Results

The results were analyzed using Multivariate Analysis of Variance (MANOVA) techniques with Mauchly's Test to verify assumptions of sphericity. Only univariate tests and results are reported here. The probability of Type I error (_) was set at 0.05 for all analyses. Error bars in the below figures represent 90% confidence intervals. Statistically significant main effects were analyzed using pairwise comparisons and the Bonferroni adjustment to determine differences among experimental conditions while controlling for inflated _. Similarly colored bars in the following graphs indicate means that were not shown to be different from each other by these pairwise comparisons. While the statistical model tested included type of maneuver and its nested levels, the results reported below are for PFD condition only. The addition of a "T" in these figures designates a transition condition.

Unusual Attitude Recovery. Statistically significant main effects of PFD were found for the following dependent variables: situation awareness ($F(4, 60) = 3.83$, $p = .01$), workload ($F(4, 60) = 4.24$, $p < .01$), and number of roll reversals ($F(4, 60) = 3.84$, $p < .01$). These results are shown in Figures 5 through 7, respectively. Pilots rated their SA higher and workload lower when using the F-16 HUD and HDD during UAR. Note that a rating of "1" on the China Lake SA Rating Scale is "Very Good" and a rating of "5" is "Very Poor". They made the fewest roll reversals when using one of the two HUD formats. Interestingly, the average number of roll reversals was highest in the HDD conditions: roughly equivalent to the two transition conditions.

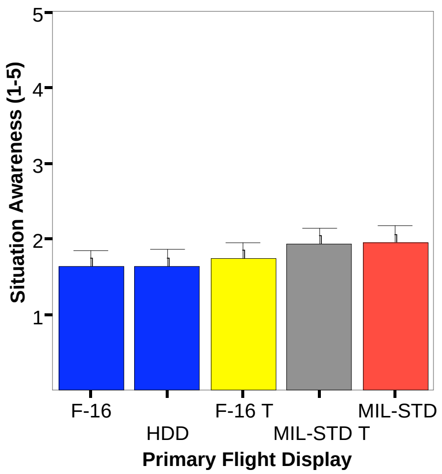

Figure 5. Effect of PFD condition on situation awareness during UAR.

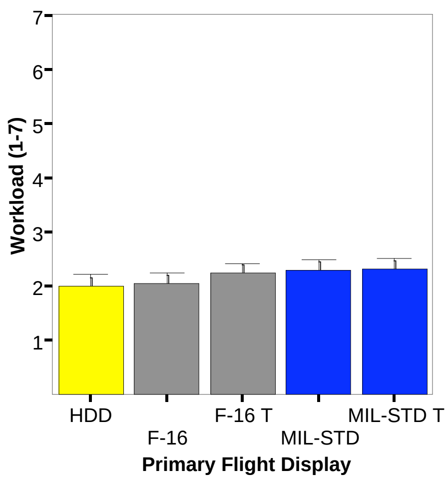

Figure 6. Effect of PFD condition on workload during UAR.

Vertical S. Statistically significant main effects of PFD were found for mean IP rating (F (4, 60) = 4.02, p = .02), situation awareness (F (4, 60) = 4.85, p < .01), workload (F (4, 60) = 4.42, p < .01), maximum airspeed deviation (F (4, 60) = 2.72, p = .04), maximum altitude deviation (F (4, 60) = 4.12, p = .02), maximum vertical velocity deviation (F (4, 60) = 9.07, p < .01), and maximum bank deviation (F (4, 60) = 2.71, p = .04). The effects on IP rating, situation awareness, workload and deviation from target vertical velocity are shown in Figures 8 through 11, respectively. Transitioning back and forth between

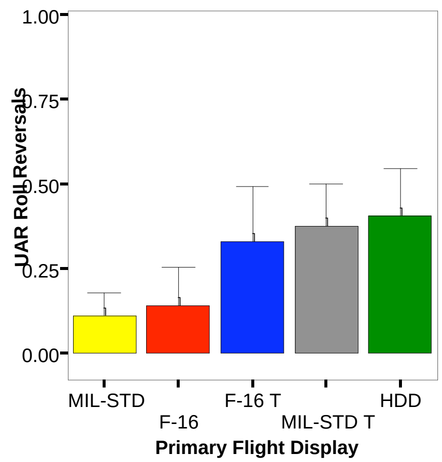

Figure 7. Effect of PFD condition on roll reversals during UAR.

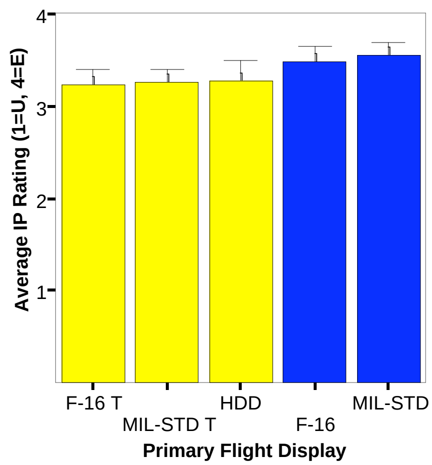

Figure 8. Effect of PFD condition on average IP rating for Vertical S.

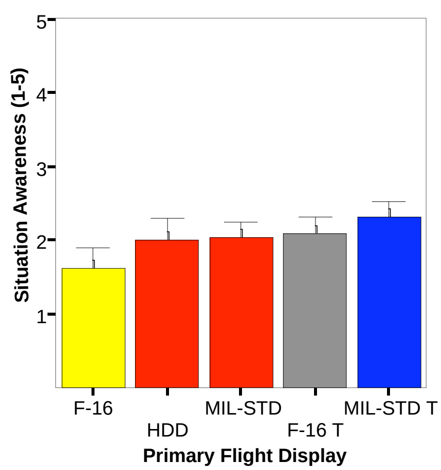

Figure 9. Effect of PFD condition on rating of situation awareness for Vertical S.

head-up and head-down PFDs had more effect on these measures than did the formats of the individual PFDs.

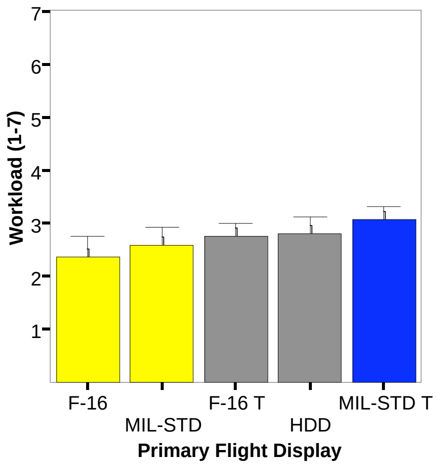

Figure 10. Effect of PFD condition on workload rating for Vertical S.

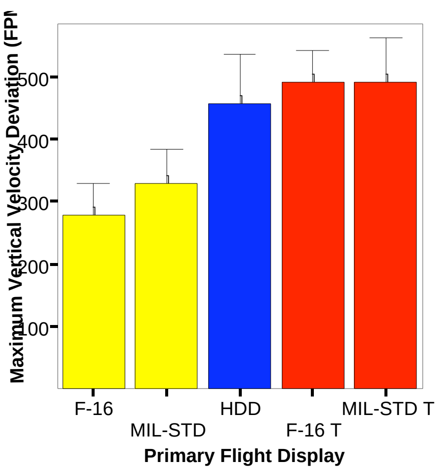

Figure 11. Effect of PFD condition on maximum vertical velocity deviation during Vertical S..

Subjective Questionnaire. Pilots were asked to rate how much they agreed (strongly disagree to strongly agree) with three statements on a seven-point scale ranging from –3 to +3. The three statements were:

1) The primary flight displays I flew today facilitated an efficient crosscheck across the displays.
2) The primary flight displays I flew today did not present conflicting cues regarding flight parameters, trends, rates of change, or display scaling.
3) The primary flight displays I flew today utilized an intuitive data manipulation scheme.

They rated the two combinations HDD and HUD separately. Means of their responses are presented in Table 1.

Table 1. Mean responses to subjective questionnaire.

	HDD & F-16 HUD	HDD & MIL-STD HUD
Facilitated Efficient Crosscheck	2.2	1.6
Did Not Present Conflicting Cues	2.0	1.3
Used An Intuitive Scheme	2.2	1.5

Comments indicated that a mismatch between vertical velocity arcs on the HDD and MIL-STD HUD was a factor in lower ratings for this combination. Several pilots also commented that the arcs were more difficult to line up with a tic mark when attempting to “nail” a specific vertical velocity during the Vertical S maneuvers.

Conclusions

The primary purpose of the study was to discover if differences among three proposed PFDs in the T-38C would have any practical effect on pilot situation awareness, workload, or performance. Given the mission of the aircraft, the effect on student pilots (minimal experience and no previous experience with a HUD) was of particular concern. In early discussions with T-38C program officials and subject-matter experts, it was agreed *a priori* that a difference of one letter grade in IP ratings or one second in initiating unusual attitude recovery would be indicators of a *practically* significant difference between PFDs. No such effects were found. Instead, performance results, ratings of situation awareness and workload, and responses to the subjective questionnaire all form a pattern indicating that differences between the three PFDs in the T-38C had little impact on the pilots in this study.

This finding was not expected: obvious differences in scale (e.g., linear vs. logarithmic) and format (tapes vs. dials) apparently did not represent inconsistencies to pilots, nor did they interfere with pilots’ instrument crosschecks. It seems that as long as basic data (i.e., digital values) are present and consistent, and as long as analog trend indications don’t move in actual contradiction to one another, pilots are able to integrate information presented head-up and head-down without difficulty. Indeed, the results of the transition conditions were often similar to those using the head-down display alone. The results support a conclusion that consistency within a PFD is more important than consistency across head-up and head-down PFDs: differences in location, color, and display medium may facilitate perceptual and attentional separation of the information displayed. It should be noted that these conclusions may not apply to higher workload situations. Throughout this study workload was rated low, situation awareness was rated high, and the grade most often given by the three IPs was "Excellent". Pilots in this study were not required to handle turbulence or distracters from the primary task of flying the aircraft.

This last point leads to another unexpected finding: no performance advantage or pilot preference was found for counterpointers over tapes – an apparent non-replication of previous studies. A comparison of tasks and pilots used in these various studies yields some possible explanations. Previous studies examining head-up tapes vs. counterpointers in a similar context (Ercoline & Gillingham, 1990; Hughes et al., 1990; Weinstein et al., 1992) have sampled pilots with extensive HUD experience, have used much more experienced pilots (commonly over 2000 hours), and have used more diverse tasks. For example, precision and non-precision approaches were not conducted in the current study. While Ercoline & Gillingham (1990) and Weinstein, Ercoline, Evans, & Bitton (1992) used Vertical S maneuvers, they added significant turbulence, presumably increasing difficulty and workload. Finally, one other very important difference should be noted: previous authors do report comparing the vertical velocity scale found in Figure 3 with the arc found in Figure 4. It seems likely that when a pilot's task is to maintain a specific vertical velocity that is an even multiple of 500 feet per minute (as in the Vertical S task), the emergent feature of a pointer lining up with a scale marker is more important than the form of the underlying analog scale. The results of the current study do replicate those of Hughes, Dudley, & Lovering (1990) in finding that UAR is affected more by pitch ladder and artificial horizon format than by the format of airspeed and altitude indicators.

The T-38C was introduced into IFF training in October 2001 and into Specialized Undergraduate Pilot Training in September 2002. At this writing, only the F-16 HUD emulation is being used to train student pilots. Introduction of the MIL-STD emulation is being delayed because: 1) There are currently no in-service USAF aircraft using MIL-STD HUD symbology, 2) Air Education and Training Command (AETC) IPs are using the interim period to gain experience with MIL-STD symbology and, 3) improvements, based on flight experience to date, are required to make the symbology useable in the T-38C (due to the relatively small field-of-view of the T-38C HUD, many pilots feel the MIL-STD format is too cluttered). The T-38C Avionics System Working Group has recommended a number of changes to reduce clutter and otherwise improve the display.

Acknowledgments

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