A COMPARISON OF HELMET-MOUNTED DISPLAY SYMBOLOGIES DURING LIVE FLIGHT OPERATIONAL TASKS

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Spatial disorientation continues to be one of the most costly problems in military aviation, as measured by both life and equipment loss. The unique Helmet-Mounted Display (HMD) centric interface within 5th generation aircraft has the potential to increase tactical capability when compared to previous similar-role aircraft. This study investigated the addition of off-axis ownship attitude information within the HMD field-of-view when the operator looks away from the virtual Head-Up Display (vHUD). In some 5th generation aircraft, traditional HUD symbology is presented via the HMD as there is no aircraft-fixed combiner. In some instances, the only attitude information included via the HMD is part of the vHUD symbology and is only available when the operator looks forward. For this study, a comparison was performed between a baseline representative symbology design and two other interfaces which included variations of off-boresight attitude information symbology. Air-to-ground tactical tasks of varying complexity were performed in live flight by evaluation pilots seated in the rear cockpit of an L-29 aircraft while donning a 5th generation representative HMD system. In addition to the HMD symbology, the visual scene presented was a virtual depiction of a mountainous terrain area. The real outside world was occluded by an opaque hood affixed to the canopy glass. Qualified pilots (n = 10) participated in the study and each flew three approximately one-hour flights. Data collection included quantitative performance, physiological response, and subjective feedback, and preliminary results are presented here.

Background

Historically, the objective of new cockpit technology development has been to enhance pilot performance (such as situation awareness) without causing problems such as Spatial Disorientation (SD). However, when improperly designed or poorly integrated, such technologies may actually reduce performance and increase the likelihood of unintended consequences. SD continues to be a serious problem in the military flight domain and it is critical that both the potential to cause problems as well as support effective defensive mitigation strategies be considered early during the development of new technologies. Past research has shown that new technologies change operator behaviors. For example, the availability of visual information provided via Helmet-Mounted Displays (HMDs) results in pilots looking farther off-axis for longer durations than when the information is not provided (Geiselman, 1999; Geiselman & Havig, 2011; Geiselman, Havig, & Brewer, 2000; Geiselman & Osgood, 1995; Post, Geiselman, & Goodyear, 1999). Presently, we are not able to accurately predict and characterize the potential traps of these behavioral changes, especially under operational conditions. There are two important usability questions which follow: 1) Applied to the 5th generation fighter representative environment, what are the potential effects of the technology on the causation of SD and are the resulting effects predictable and, 2) can effective mitigation strategies be designed into the system to minimize unintended consequences of the technology use?

Test Objectives

The overall aim of this project was to develop and test symbologies that support prevention of Spatial Disorientation (SD) during tactical off-boresight (OBS) use of an HMD in a fighter aircraft platform. Specific aims of this effort included the development of scenarios that are anticipated to cause SD in a 5th generation fighter platform using an HMD and evaluation/refinement of OBS HMD symbology configurations subjected to a high dynamics airborne evaluation.

Experimental Apparatus

A 5th generation fighter aircraft representative HMD was integrated in an OPL L-29 instrumented flight test aircraft and connected to a head-tracked graphics processor that served as a simulated Distributed Aperture System (DAS) for use in actual flight. While wearing the HMD the Evaluation Pilots (EPs) experienced a highly realistic nighttime Close Air Support (CAS) scenario while operating the L-29 aircraft from the back seat crew station as if they were in a single seat 5th generation HMD fighter environment (see Figure 1).

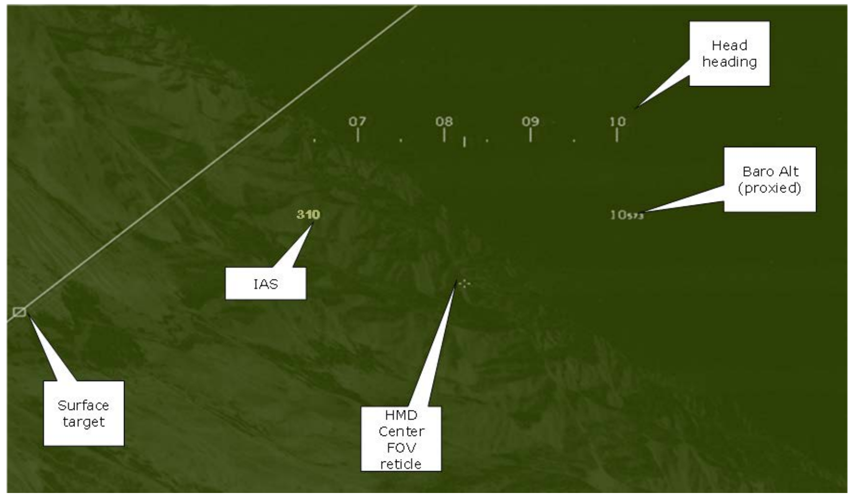
Figure 1. Fifth Generation Fighter HMD Integrated in OPL's L-29 Flight Testbed

The two OPL L-29 aircraft are single engine, tandem-seat fighter jet trainers with pressurized cockpits. These aircraft are fully acrobatic and capable of performing high dynamic maneuvers up to +8/-4gz at speeds up to Mach 0.7. These testbeds are highly instrumented aircraft that use state of the art avionics that incorporate onboard and netcentric airwarfare simulation capabilities, weapon models, Fire Control Radar simulation, and HMD capabilities. Additionally, the aircraft are equipped with human performance state assessment equipment which allows for monitoring of EP physiological based cognitive workload parameters, control inputs, and 6 channel audio/visual recording for human factors assessments. The aircraft are instrumented in such a way that they can also serve as aircraft-in-the-loop (AIL) simulators. The AIL capability was extensively used on the ground to train the EPs on the symbology and L-29 EP crew duties. For live flight operations, the Safety Pilot (SP) performed the taxi-operations, takeoff, and landings from the front seat. The EP crew station canopy was covered with a sliding cloth hood to eliminate the view of the "real-world" outside. A lateral and vertical position proxy mechanism allowed operation of the L-29 in Iowa airspace at mid-teen flight levels, while the EP experienced a nighttime, low-level DAS (monochrome shades of green) environment corresponding to an operations area in a mountainous region of Afghanistan. A ground based Joint Terminal Attack Controller (JTAC) used an immersive graphics environment of the same Afghan battlespace as seen from a ground soldier perspective to coordinate simulated airstrikes on a variety of target areas.

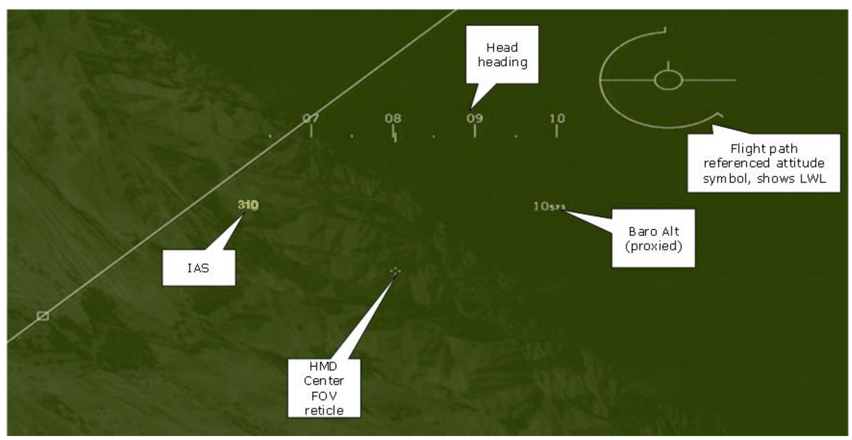
Experimental Procedures and Symbologies

Both the airborne EP fighter pilot and the ground based JTAC used a local area map-like product that we referred to as a placemat. It showed numbered buildings of tactical interest and road names for standardized situation awareness in the "keyhole" CAS procedures. Keyhole CAS uses a standardized template of the target area and initial points. EPs were given a coordinate designation of the Echo point (general target area) that could be visualized in the HMD as a superimposed target diamond and Azimuth Steering Line (ASL). A talk-on to the target selected by the JTAC followed the issuance of a standardized nine-line brief. The talk-on made frequent reference to features on the placemat product carried onboard by the EP and generally worked from large visible features such as the main river and highways to smaller features such as numbered buildings. During the talk-on, the EP was given altitude block assignments of increasing tightness to require attentional division between airmanship and weaponeering with a large percentage of the time spent looking OBS to visually identify target features in the DAS. The talk-on, requiring long and frequent OBS head movements, provided the majority of data of interest to our team. Specifically, we were interested in assessing EP airmanship, weaponeering, situation awareness, and cognitive workload, as a function of three different OBS symbology formats in the HMD. We assessed the comparative potential of those symbologies to prevent loss of spatial orientation. The airborne and ground based battlespaces were synchronized through a High Level Architecture Distributed Interactive Simulation (HLA/DIS) data protocol carried on a tactical utility data link from a ground station to the aircraft. A Rockwell Collins Live Virtual Constructive (LVC) avionics load was used to simulate the weapon flyout models that provided realistic ground attack weapons cueing on the Virtual Head Up Display (vHUD) in the HMD and tactical situation awareness as well as weapons Stores Management System on the Head Down Display. The three different OBS HMD test symbologies assessed were: 1). Current Display Format (CDF, see Figure 2), 2). Distributed Flight Path Reference (DFR, see Figure 3), and 3). Non-Distributed Flight Path Reference (NDFR, see Figure 4). It is important to note that the graphics generator output was in full color (see Figure 1, picture with mountains) and was fed into the fighter HMD that had green

Organic LED imagers. Figures 2-4 were manipulated to dim the background image to highlight the symbology and the background was tinted green to illustrate what the color image would have looked like through the green monochrome HMD. The EPs therefore saw the image on the HMD's combiner as a biocular, fully overlapped monochrome green picture of 1280 x 1024 pixels on a 30 x 40 degrees field of view. The OBS symbologies were shown when the EP turned his head more than 15 degrees laterally or tilted his head by more than 25 degrees vertically from the aircraft forward center line. In the CDF (Figure 2) symbology, there was no attitude (climb/dive/roll) information available. Only speed, head heading, and altitude were shown. Pilots thus had to look in the forward direction to the vHUD or interpret the rate of change in speed, heading, and altitude readouts to obtain aircraft attitude information, which is a difficult and error prone process. The DFR symbology (Figure 3) added aircraft attitude information in the upper right corner of the HMD field of view. This feature had a fixed aircraft symbol with a movable earth reference circle that rotated around the symbol center with regard to bank angle and which grew or shrank with regard to flightpath angle (climb/dive vs. pitch). The earth reference circle had two end-tick marks that referenced the nearest horizon on each side. Thus, for a flight path that pointed straight up or nearly so, the earth circle perimeter was small to non-existent, with only the end-tick marks left, thus indicating that the aircraft was in a climb attitude. For a flight path that pointed straight down or nearly so, the earth reference was a nearly full circle, thus indicating that there was no sky left around the forward direction and that the aircraft was in a dive attitude. The end-tick marks indicated the direction of the nearest horizon. In a level flight-path attitude, the earth reference was a semi-circle. For a full description of the symbology mechanization, see (Geiselman, 1999).

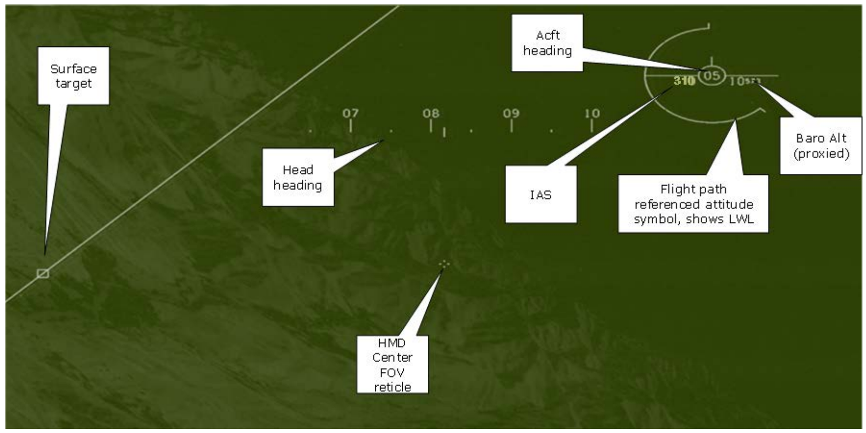


Note: Green background dimmed to illustrate symbology.
Figure 2. *Current Display Format (CDF) Seen During Off-Boresight Head movements*



Note: Green background dimmed to illustrate symbology.
Figure 3. *Distributed Flight Path Reference (DFR) seen During Off-Boresight Head movements*

In the NDFR symbology case (see Figure 4), the flight path reference symbol in the upper right corner of the OBS HMD field of view (FOV) was furnished with flight information readouts. These included airspeed on the left wing of the aircraft symbol, aircraft heading as a two-digit number in the center circle, and altitude (MSL) on the right wing of the aircraft symbol. In this configuration, the corresponding flight information readouts were removed from the central section of the HMD FOV. The design of experiments (DOE) plan involved a total of ten current military pilots with jet aircraft experience and training or combat experience with air-to-ground (A/G) attack doctrine. We planned to enroll these ten EPs from two equally sized strata with five having prior HMD experience (e.g. Joint Helmet, F-35, or Scorpion) and five EPs having no such experience. In executing this project, we ended up with a sample of three EPs who had prior HMD experience and seven EPs who did not. The DOE also planned for three sorties per EP. In executing the flights, we ended up with nine EPs who flew all three sorties, one EP who flew only one sortie but then contracted a head cold and elected not to continue, and one EP who made up the remaining two sorties. Since these sorties were representative of nighttime CAS, we refer to them as sorties N1, N2, and N3, in increasing order of intended difficulty. Within each sortie, three attack scenarios were executed so that all three symbologies (CDF, DFR, NDFR) were used for a full A/G attack profile each. During the first scenario of each sortie, the EP checked in with the JTAC, call-sign SWIFT 06 as fragged (as stated by the briefed simulated air tasking order). The JTAC then provided a situation report (SITREP), issued an altitude clearance limit, and provided a nine-line for the first attack. Following issuance of the nine-line, the JTAC provided a visual talk-on to the intended first target using visual references that were available on the placemat product and which the EP had to identify visually using the HMD DAS. The CAS left-orbit stack altitude clearance limits were as follows N1: Remain above 9,000 ft, N2: Remain above 9,000 ft and clear of clouds, with an overcast cloud deck at 13,000, and N3: Remain in a block of 9,000 ft to 11,000 ft. During the talk-on, the EP had to maintain the altitude block in the CAS stack and maneuver the aircraft in such a way as to facilitate visual identification of the target. Once the target was identified, the JTAC requested immediate time-on-target (TOT) for either a show-of-force (SOF) or a bomb-on-target (BOT) delivery. This request also cleared the EP off the CAS stack. The EP then performed the necessary weaponeering and maneuvering to execute the SOF or employ a Mk-82 bomb on the target using a Continuous Computed Impact Point delivery method. Following completion of the necessary attacks, the JTAC asked the EP to provide subjective workload ratings on the Bedford rating scale (1=low, 10=very high) and a 3D Situation Awareness Rating Technique (SART) rating.



Note: Green background dimmed to illustrate symbology.

Figure 4. Non-Distributed Flight Path Reference (NDFR) seen During Off-Boresight Head movements

Results & Discussion

The following is a small sample of preliminary results as data analysis is still ongoing. This section is intended to provide an initial look at potentially important trends driving further analysis. We specifically chose to include head-tracking and workload data to illustrate the value of off-boresight attitude information. We examined data in three specific time periods of interest within individual attack scenarios based on the likelihood of OBS head movements: 1) SITREP/Nine-Line – the period when the JTAC issued the situation report or Nine-Line, 2) Talk-On start to Talk-On complete, and 3) Total Attack – from Talk-On start to weapons release or SOF complete. The Total Attack time period is thus basically a summary of the tactical (non-administrative) part of the CAS. We noticed that during the SITREP/Nine-Line, EPs were often focused on kneeboard and chart products to the apparent detriment of fine control of the aircraft. A look into the cockpit toward a kneeboard is an OBS look and the DFR and NDFR symbologies are believed to be beneficial in that regime. Additionally, during the Talk-On, EPs are looking frequently OBS to the left to identify landmarks and features in the DAS image. We believe that the DFR and NDFR attitude symbols are very useful for that phase of operation as well. Figure 5 is a collection of "heat maps" produced from head-tracker data. These show aggregated head positions for all subjects by aforementioned time periods of interest and symbology format. The higher density pixels indicate a higher number of head counts in the 1x1 degree region. Each map extends +/- 90 degrees in x (lateral) and y (vertical) axes. The red outlined box in the center of each map indicates the vHUD FOV (15 degrees lateral by 25 degrees vertical). We characterized EP cross-check behavior with a series of measures relating to the head movements OBS (see Table 1). Specifically, we analyzed cross-check rate, which in Table 1, we define as the number of times per minute the EP transitions from inside, to outside, to back inside of the vHUD FOV. Further, we include the total time spent OBS and the average duration of each single "look" during the time period of interest. From the heat maps, we notice a qualitative difference between CDF, DFR, and NDFR in the spread of the head-center orientation toward the kneeboard (4 o'clock position on the heat maps) during the SITREP/Nine-Line phase. There appears to be a tighter focus (better concentration ability) on the kneeboard, presumably better supported by the NDFR symbology when compared to the CDF.

Table 1. *Off-Boresight Look Metrics for Time Periods of Interest.*

SITREP/9-Line OBS Look Metrics - Aggregate for All Sorties						
Symbology	CDF		DFR		NDFR	
	Mean	SD	Mean	SD	Mean	SD
OBS Looks/Minute	12.20	5.08	10.19	5.18	11.28	6.53
%Time OBS	37.33	15.85	37.01	17.19	36.19	19.15
Avg. OBS Look Dur.	2.00	1.34	2.51	1.75	2.02	1.28
Talk-On OBS Look Metrics - Aggregate for All Sorties						
Symbology	CDF		DFR		NDFR	
	Mean	SD	Mean	SD	Mean	SD
OBS Looks/Minute	8.38	3.30	7.35	4.76	7.53	4.25
%Time OBS	47.12	25.03	41.30	23.63	47.66	25.20
Avg. OBS Look Dur.	3.46	2.27	4.14	3.78	4.12	3.05
Total Attack OBS Look Metrics - Aggregate for All Sorties						
Symbology	CDF		DFR		NDFR	
	Mean	SD	Mean	SD	Mean	SD
OBS Looks/Minute	6.84	2.69	5.55	2.50	5.95	2.87
%Time OBS	34.31	17.80	33.01	19.00	37.02	21.44
Avg. OBS Look Dur.	3.04	1.60	3.54	2.27	3.96	2.68

The heat maps for the Talk-On phase clearly show that EPs were able to venture OBS farther more often, and in a more organized (stratified) way with the NDFR when compared to the CDF. The DFR was in the middle of that trend, meaning that EPs went OBS a little more often and somewhat farther under the DFR condition when compared to the CDF condition. This is confirmed with the basic statistics in Table 1 for the Talk-On phase in that the DFR and NDFR symbology enabled the EPs to get the Talk-On job done with fewer OBS head movements of longer duration when compared to the CDF. This enabling capability of the DFR and NDFR is practically significant as the more frequent disruption of the search task in the CDF costs the EPs extra time to re-acquire the Talk-On targets. The large spread of the OBS head movements in the CDF illustrate the struggle that EPs faced in re-acquisition of the Talk-On targets after a check-look to the vHUD (forward direction).

Table 2. *Mean Bedford Workload and SART Situation Awareness Scores*

	Bedford	SART
CDF	4.75	7.0
DFR	4.0	7.75
NDFR	4.0	8.0*

* denotes statistically significant difference to CDF

Bedford workload and situation awareness ratings were provided by the 10 EPs after each attack, and the mean scores are shown in Table 2. A Kolmogorov-Smirnov test indicated that the normality assumption could be made for the Bedford data (KS=0.03, $p>0.15$) and the SART data (KS=0.021, $p>0.15$). ANOVA did not indicate any statistically significant differences in the mean Bedford workload ratings. The ANOVA on the SART ratings indicated a statistically significant ($F_{2,78}=5.99$, $p=0.004$) effect for the symbology factor. A pairwise post-hoc t-test on the differences in effect means indicated that the NDFR ratings were significantly higher ($t=3.43$, $p=0.0027$) than their CDF counterparts. That same trend for the DFR was not quite significant ($t=2.03$, $p=0.11$), nor was the difference between DFR and NDFR.

While certainly preliminary, the results of this current live-flight study lend support to previous findings that HMD use results in pilots looking OBS for longer durations (Geiselman et al., 2000). Within the heat maps, there is evidence of an improved structure to the Talk-On scan behavior in the DFR and NDFR conditions. The SART ratings indicate that an advantage was provided by the NDFR format as well. Future analyses of this dataset will look for any instances of SD, examine the objective airmanship and weaponeering data, and apply metrics that better characterize the spread of the data in the heat maps. The results of those analyses will inform empirically based recommendations for the design of HMD symbology that improves pilot performance and mission effectiveness during tactically challenging operations with 5th generation fighter HMDs.

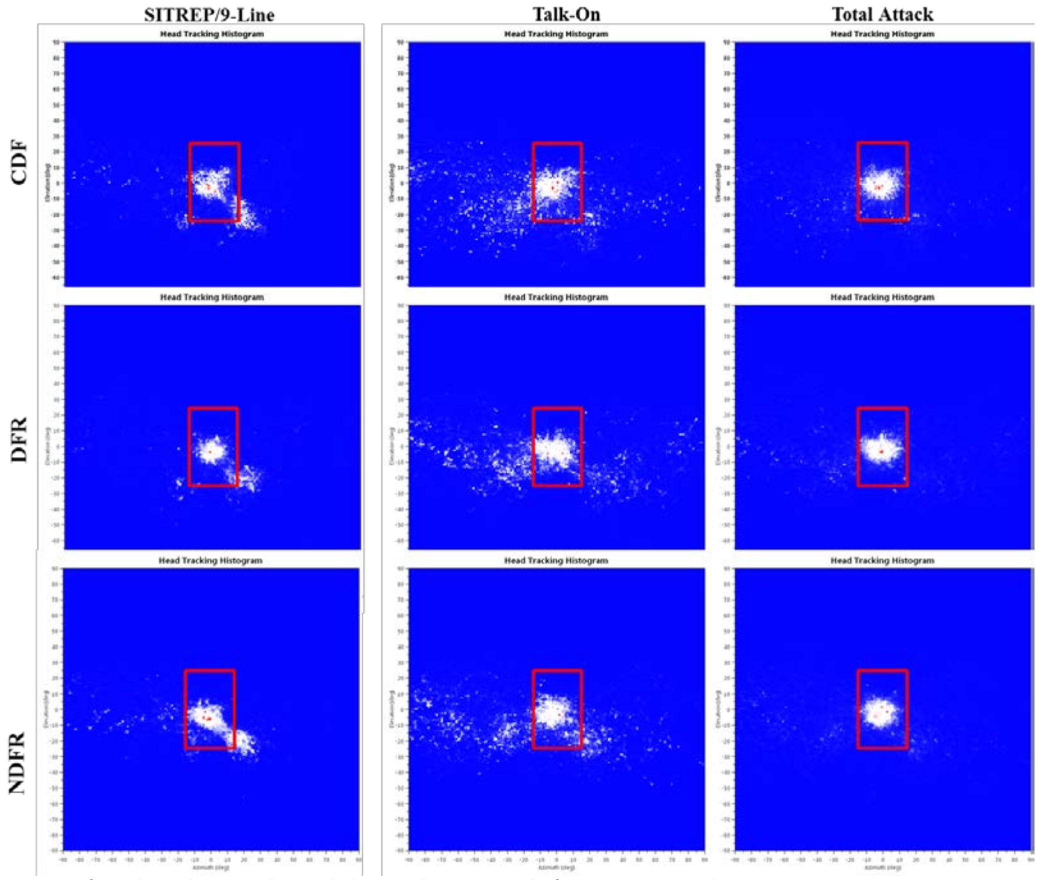


Figure 5. Heat Maps of Head Tracker Data by Symbology and Time period of Interest, N=10 Pilots.

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