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The Efficacy of Advanced Visual Display Technologies in Simulated Airborne Command and Control Environments

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Abstract

Increases in information availability have elevated the issue of display cluttering in application domains in which display space is limited. To remediate this problem, evaluations of potential display technologies should be conducted. This paper discusses the examination of head-mounted displays (HMDs) and a multi-layer display (MLD) in a simulated airborne command and control environment. Eight participants engaged in tasks in which they were required to retrieve information presented on one of several display technologies. This information was available via two types of HMD, on paper, on the MLD, or on the primary display. The results indicated that the HMDs and MLD tested did not in general deliver a performance benefit over the other methods of information retrieval. However, the MLD did produce a decrease in the subjective rating of mental workload and a perceived improvement on several post-experimental scales.

Introduction

Command and control (C2) is defined by US Air Force doctrine as "the exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission" (US Air Force, 1997, pp. 79-80). At the tactical level, C2 for air assets in the US Air Force is accomplished by the weapons section of an Airborne Warning and Control System (AWACS) or Joint Surveillance and Target Attack Radar System (JSTARS), or an analogous ground-based platform (Williams, 1997). Although the missions of these systems are not identical, there is significant overlap in the roles of the weapons section personnel assigned to them. These air battle managers are responsible for the tactical direction of air assets involved in strategic attack, interdiction, counter-air, and close support missions, and the coordination of activities such as air refueling and combat search and rescue. Although most of the direction and coordination is done by means of voice communications, the situation awareness (SA) required to do them well is provided almost exclusively through the visual modality, either on a display monitor or on printed media.

The control of air assets occurs over space and time, and the primary display used to accomplish the task is a dynamic geospatial display (GD): a two-dimensional projection of an area of responsibility augmented with visual representations of air, ground, and surface tracks, political and geographical demarcations, and additional mission-relevant symbology. In older systems, most information required to complete the mission that is not depicted on the GD is obtained by voice communication with off-board assets or via paper media transported onto the platform, such as the printed version of the air tasking order. In current and future systems, such information will be available to the operator in electronic formats that may provide more efficient modes of information retrieval.

Among the greatest of problems posed by the electronic display of information is the potential for display clutter. The GD is one of the principal sources of SA for an air battle manager, and continuous uncluttered visibility thereto is critical to mission success (Nelson & Bolia, 2005). This presents a dilemma for the designer: where should non-geospatial mission-critical information be presented, if not within a window sitting atop the GD?

The most obvious answer is to provide each operator with a secondary visual display. While this has been done frequently and to good effect in ground-based platforms, it has proven impractical for airborne systems, where weight and space are at a premium. Two additional display concepts have been proposed: head-mounted displays (HMDs) and transparent multi-layer displays (MLDs). Both have been investigated to a limited extent in the context of airborne tactical C2.

Despite their shortcomings, which include field-of-view limitations, eyestrain, head and neck discomfort, and the potential to promote sickness, HMDs have found acceptance in certain operational communities. The primary advantage that they offer is the capacity for information portrayal regardless of the orientation of the operator's head. In addition, see-through HMDs may afford an air battle manager the ability to view auxiliary information on an HMD without obfuscating his or her GD.

Galster and his colleagues (Galster, Brown, Miller, & Tollner, 2005) examined the effects of electronic display formats on primary and secondary task performance in a simulated air battle management environment. Their finding that performance on both the primary mission task – retasking a strike package – and several secondary tasks was better when the secondary tasks were accomplished using information gleaned from traditional paper documents was somewhat surprising, but was hypothesized to be the result of the low complexity of the secondary tasks performed. In a subsequent study (Galster, Bolia, Brown, & Tollner, 2005), task complexity was manipulated as an independent variable, and this supposition was confirmed. However, although the electronic displays – on-screen presentation and presentation on two varieties of HMDs – were not out-performed by the paper documents, neither did the investigation discriminate between them. While this failure may point to a legitimate equivalence between the display formats, it may also be indicative of limitations on the difficulty of the primary task, or in the resolution of the HMDs.

A second proposed technology solution is the MLD, a device comprising a transparent liquid crystal display (LCD) mounted at a fixed distance in front of a parallel opaque LCD. This allows information portrayal on two displays simultaneously, and has two potential advantages. First, the information on the foreground plane may be displayed with varying degrees of transparency, allowing the operator to see-through any pop-up displays of auxiliary information to the underlying GD. Second, the separation between the two displays leverages the human visual system's capacity to use depth as a segregation mechanism, which may enhance the MLD's ability to declutter the operator's display.

Bolia, Nelson, and Vidulich (2004) speculated that an MLD might be used to increase performance on both situation tracking and secondary information retrieval in tasks analogous to those performed by air battle managers. They used a multiple-element tracking task to represent the GD and an arithmetic comparison task as a secondary task to study this hypothesis, and manipulated both depth and transparency. The results of the study suggested that transparency improved performance and reduced workload, but that depth was not a significant source of variance. However, it is possible that the abstract tasks employed did not faithfully replicate the conditions under which, in a more cluttered simulation, depth might provide an effective cue.

The purpose of the present investigation was to extend previous work examining both technologies for their potential to ameliorate the clutter problem. This is distinguished from earlier experiments by the use of higher-resolution HMDs, on the one hand, and a more faithful representation of an air battle management environment, on the other.

Method

Participants

Five males and three females between the ages of 18 and 34 (*M* = 22.75 years, *SE* = 1.79 years) participated in the experiment. All participants reported normal or corrected-to-normal vision in both eyes. Individuals were paid for their participation.

Apparatus

The study was conducted in a medium-fidelity simulated Airborne Warning and Control System (AWACS) environment consisting of six PC-based operator workstations each with a 19" flat panel-display. However, only one operator workstation was needed to conduct this study and all of the mission scenarios were presented on an MLD. A stereo headset was worn by the participant for listening to audio communications, tones and alerts.

The Solipsys Tactical Display Format (TDF) software (Conn, 2003) was used to generate the operator's GD. Modular Semi-Automated Forces, or ModSAF (ModSAF 5.0, Advanced Distributed Simulation Technology, 1999), was used to create and provide the simulated air and ground assets displayed by the TDF software.

The 18mxG MLD, manufactured by Deep Video Imaging, consisted of two 18.1 inch LCD planes mounted one in front of the other. The 2 planes (foreground and background) are separated by 12 mm and both planes have 24-bit colour depth and a resolution of 1280 × 1024. Images presented on the foreground plane were transparent. Transparency was achieved using the OpenGL alpha blending technique, which averages pixels from two display elements in the display buffer to create a "see-through" appearance.

Two commercially available HMDs were evaluated during the experiment. The Shimadzu DataGlass 2/A is an SVGA display with a colour LCD that presents a full-size image right in front of the eye (either right or left eye). It provides a 30-degree field of view with a resolution of 800 × 600. The other HMD, an I-O Display Systems I-Glasses SVGA Pro binocular HMD, is a small, lightweight (< 7 oz) head-wearable display with a 26-degree field of view and a resolution of 800 × 600. The display was attached to an I-Glasses Mounting System to promote stability, comfort and flipping–up of the display.

For each mission scenario, the participant's GD, video of the participant performing the task, and the audio communications and tones were recorded to a DVD for post-experimental review.

Mission Tasks

Participants were asked to control an air battle involving the re-targeting of strike aircraft. They were required to perform distance measurements and calculations to determine if strike aircraft could be re-directed to various targets and/or an air refueller using information provided on a re-targeting form. This task appeared on the monitor as a set of 4 pop-up windows beginning approximately 2.5 minutes after the inception of each mission. Each pop-up window contained a re-targeting question and response buttons for affirmative and negative responses. There were two types of re-targeting questions. Type I questions asked "Can an aircraft strike a different target and still make its planned refueling time?" Type II questions asked "Can an aircraft go directly to its air refueller and then strike a designated target by a given time?"

To perform the re-targeting tasks the participants were required to look up strike aircraft call signs, preplanned air refuellers and planned refueling times on the re-targeting form. The participants also needed to determine distances using the TDF measurement features. Worksheets and a calculator were provided for use by the participants.

Four times throughout each mission, a radio frequency call occurred (2 via audio and 2 via a visually displayed message), requiring the participant to look up and enter a new radio frequency from a radio frequency form. For the 2 audio calls, the participant received a message over the headphones requesting a report of a new radio frequency for one of the following: 1) CSAR, 2) Command, 3) Defence, or 4) Strike personnel. An example of an audio call is "press blue 5 on Command". The participant would click on the Command button on the radio panel and then look up and enter the fifth corresponding frequency under the column labeled blue. The remaining 2 radio calls were displayed as a text message on the radio panel.

The participant also received four Situation Awareness probes consisting of 2 altitude and 2 heading tasks requiring the participant to search for and report a specific aircraft's altitude or heading using the TDF display features. At random times during each mission, a pop-up window would appear asking for the altitude or the heading of an aircraft by call sign. The participants' task was to find the appropriate aircraft and place the cursor over it. A window in the lower left corner of the GD would appear and display the altitude and the heading of the aircraft.

Additionally, each participant was required to perform 4 dictionary wordlist tasks presented throughout each mission scenario. This task required a participant to look up a specific word and report a 10-digit code associated with that word. The dictionary wordlist consisted of a 109 page (double-sided) document of words for the paper missions or a 12,387 word Excel spreadsheet for the primary display, MLD and HMD mission scenarios.

Participants were informed that they could scroll through or perform a "Find" operation to look up words from the dictionary wordlist when using an electronically presented dictionary. In addition, participants were informed they could either type in the 10-digit code or "Copy and Paste" the code.

A tone occurred to indicate the initiation of each task as it was displayed on the monitor. The presentation of the 3 forms for each mission included one of the possible display technologies (paper forms, forms displayed on the primary display, forms displayed on the MLD, forms displayed on the monocular HMD and forms displayed on the binocular HMD). The 3 forms (electronic version) were each a separate worksheet included in an Excel workbook requiring the participant to select the proper tab for each worksheet. During the MLD missions, the forms in the Excel workbook and the "Find" window were displayed on the foreground plane using the transparency effect. The GD and radio panel were displayed on the background plane. During non-MLD missions, the foreground panel was disabled.

Training was performed at the beginning of each participant's session and lasted approximately 2 hours. Upon arrival to the laboratory, a brief description of AWACS aircraft and AWACS operator missions was given. All participants then received a training protocol that was divided into three functional areas; 1) operator workstation and GD control; 2) re-targeting task training without the secondary tasks; and 3) re-targeting task training with secondary tasks. A mission clock was running (10 minutes) during the training missions, but the participants were given as much time as needed to finish all of the tasks.

During training it was explained to the participants that the primary task (re-targeting with distance measuring and calculations) was the highest priority task. However, they were told not to ignore or disregard the secondary tasks, and were instructed to develop strategies to aid in completion of all the tasks in the allotted 10 minute mission time.

Experimental Design

A within-subjects experimental design was employed. Display technology (paper forms, forms displayed on the primary display, forms displayed on the MLD, forms displayed on the monocular HMD and forms displayed on the binocular HMD) was the manipulated independent variable. Performance scores and completion times for each of the tasks served as dependent measures. Each participant completed 4 missions using each display technology for a total of 20 mission scenarios. The maximum duration of each mission was 10 minutes. Upon completion of each mission, participants were asked to rate their perceived mental workload and, situational awareness (SA). The entire experiment, including training, had a duration of approximately 6 hours for each participant.

The NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988) sub-scales were used for ratings of mental workload. The Measures of Situation Awareness (3-D SART) questionnaire (Taylor, 1990), with an additional question asking the participants to rate their overall SA, was also administered.

At the end of the experiment, participants were asked to rate each of the display conditions for the following characteristics: mental workload, temporal demand, physical demand, performance, effort, frustration, ability to complete the task, level of comfort, convenience of use, ease of use, eye fatigue and time demand. This measure was different than the previous subjective measures in that 1) It was administered at the end of the experiment rather than at the end of each trial; and 2) A likert scale from 0-5 was used for all responses.

Results

Primary Task Performance

The data collected during the trials were analyzed using a 4 (display technology) single factor analysis of variance. In this and all subsequent analyses, the Huynh-Feldt procedure to correct for violations of the sphericity assumption was utilized. The results of the ANOVA conducted for the primary task indicated that there was not a significant difference in either response accuracy or response time for the different display technologies in the participant's ability to respond to the re-tasking of the strike aircraft ($p > .05$). For all conditions, correct response accuracy varied between 88% and 90%.

Secondary Task Performance

A similar statistical strategy was employed for the percent correct and response times for the secondary tasks. The results indicated that there was a significant main effect of display format for the dictionary wordlist task, $F(4, 28) = 6.59$, $p < .01$. Participants were able to look-up words and enter the associated code most accurately when retrieving that information via the monocular HMD (92.97%). This was followed by the primary display and MLD (tied at 90.63%), the binocular HMD (89.06%), and finally, the paper version (72.66%). There was not, however, a notable difference in the response times for this task.

For the Situation Awareness probe, the data suggests that the display condition did not significantly differentiate the participant's ability to respond correctly or the time to make those responses. The radio frequency task results were similarly unremarkable.

Subjective Measures

The NASA-TLX sub-scale scores were averaged to yield one workload score for each trial. This score was used in an ANOVA analogous to that described previously. The results indicated that there was a significant main effect of display technology on workload ratings, $F(4, 28) = 3.87, p < .05$. This effect, illustrated in Figure 1, indicates that participants rated their workload highest while using the paper to retrieve the required information, followed by the binocular HMD, the monocular HMD, the primary display, and lowest for the MLD condition. Participant ratings of Situation Awareness failed to differ significantly for the display technology utilized.

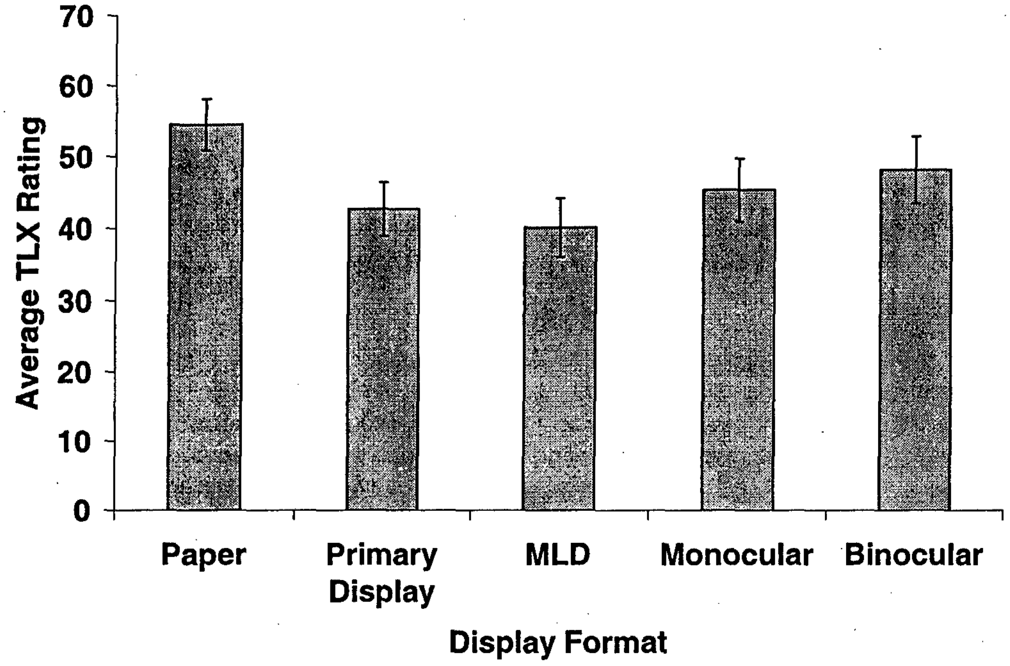

Figure 1. Average workload ratings as a function of display format.

Post Experimental Debriefing

The post experimental survey responses, all of which took on values between 0 and 5, were each subjected to a single factor analysis of variance, using the Huynh-Feldt procedure to correct for violations of the sphericity assumption. *F*-values for each of the twelve analyses, presented in Table 1, indicate a significant main effect of display format. The results of post-hoc *t*-tests adjusted with Bonferroni correction for multiple tests are presented in Table 2. While there were some differences between scales, the results were on the whole very consistent, and indicate a preference for a traditional computer monitor or an MLD over the use of paper documentation or either variety of HMD. Moreover, the two types of HMDs failed to evoke a subjective discrimination between them.

Scale	*F*(4, 28)
Mental Demand	20.65
Temporal Demand	15.40
Physical Demand	22.09
Performance	16.58
Effort	8.34
Frustration	8.14
Ability to Complete Task	15.63
Level of Comfort	38.71
Convenient to Use	4.26
Ease of Use	8.88
Eye Fatigue	26.43
Time Demand	10.37

Table 1. *F*-statistics for ANOVAs

Scale	P *vs* S	P *vs* MLD	P *vs* M-HMD	Paper *vs* – B-HMD	S *vs* MLD	S *vs* M-HMD	S *vs* B-HMD	MLD *vs* M-HMD	MLD *vs* B-HMD	M-HMD *vs* B-HMD
Mental Demand	*	*					*	*	*	
Temporal Demand	*	*	*					*	*	
Physical Demand	*	*			*	*			*	
Performance	*	*					*		*	
Effort	*	*						*	*	
Frustration	*	*							*	
Ability to Complete Task	*	*						*	*	
Level of Comfort	*	*				*	*	*	*	
Convenient to Use	*	*								
Ease of Use							*		*	
Eye Fatigue				*		*	*	*	*	
Time Demand	*	*							*	

Table 2. Significance matrix for post-hoc comparisons. (P = paper, S = screen, MLD = multi-layer display, M-HMD = monocular head mounted display, B-HMD = binocular head mounted display). * indicates comparison was significant.

Although these categories are not ranked, there is particular interest in the participant's ratings of their ability to complete the task with each display format. Figure 2 illustrates the ratings for this scale. Further, it is noteworthy to point out that the pattern of responses illustrated in Figure 2 was present in all of the rating category scales.

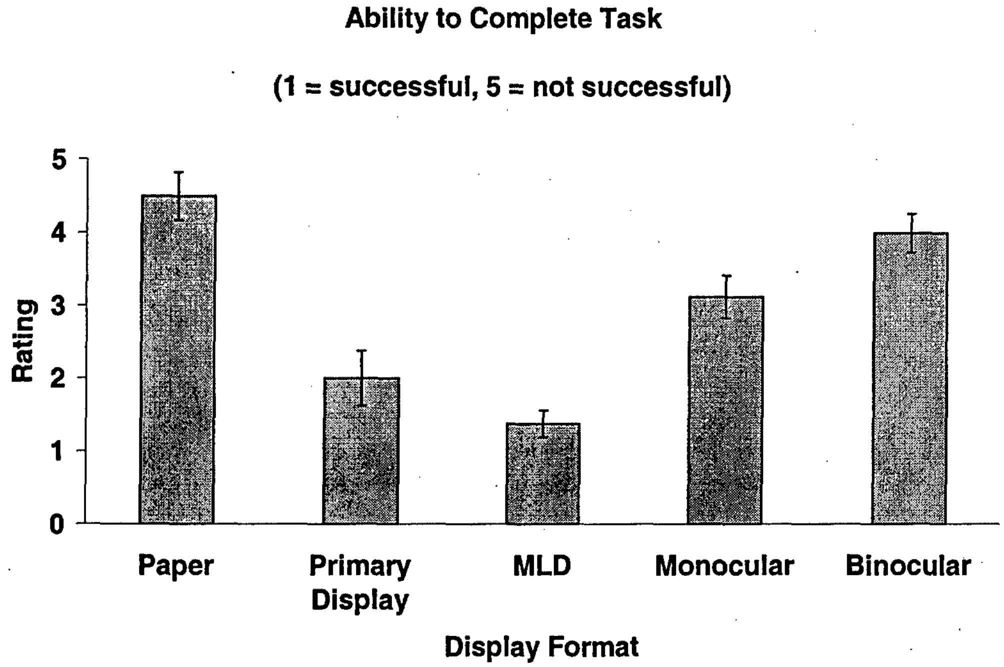

Figure 2. Participant's subjective rating of their ability to complete the entire task as a function of display format.

Discussion

This experiment represents the third evaluation of alternative display formats in a simulated command and control task environment. The focus of these experiments has been to determine whether these technologies are at a stage of maturity that may offer a benefit to tactical air battle managers in airborne platforms. The collective results indicate that if the tasks required are simple in nature, obtaining the information to conduct those tasks can easily be gleaned from using paper. However, as the tasks become more complex, the paper advantage diminishes and performance on the required tasks, on average, becomes homogeneous. This experiment was different from the first two in that two of the latest models of HMDs available were used, and the MLD was introduced as an alternative display technology.

The results of this experiment indicated that there was not a significant difference in the primary or secondary tasks, excepting the difference in the percentage of correct responses for the dictionary word look-up task. What is interesting is the change in the subjective workload associated with the change in task complexity and the addition of the MLD. In the second experiment, the average reported workload for the paper condition increased to a non-discriminate level, just as performance did, as the complexity of the tasks increased. In this experiment, participants reported lower workload levels when the alternative display formats were utilized, at least when compared to the paper condition. Moreover, the MLD condition was rated as engendering the least amount of workload by the participants. Further, this post trial rating was analogous to the ratings that participants offered at the conclusion of the entire experiment. In sum, this suggests that while there may not be a significant benefit to utilizing the MLD display from a performance standpoint, the data indicates that operators prefer that display and subjectively rate their workload as being lower and their ability to perform the required tasks as higher when operating in that condition. The next challenge will be to examine the results as the task complexity increases and becomes more aligned with real-world tasks performed by tactical air battle managers.

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