Depth of Focus and Perceived Blurring of Simultaneously-Viewed Displays

Marc D. Winterbottom
Air Force Research Laboratory, Mesa, AZ
Marc.Winterbottom@mesa.afmc.af.mil

Robert Patterson
Washington State University, Pullman, WA
rpatter@mail.wsu.edu

Byron J. Pierce, Christine Covas
Air Force Research Laboratory, Mesa, AZ
Byron.Pierce@mesa.afmc.af.mil,
Christine.Covas@mesa.afmc.af.mil

Jennifer Winner
Link Simulation and Training, Mesa, AZ
Jennifer.Winner@mesa.afmc.af.mil

ABSTRACT

Head-mounted displays (HMDs) have not previously been combined with flat-panel display systems and it was unknown whether viewing two displays at differing focal plane distances would lead to perceived blurring or visual discomfort. This is now a concern as the Joint Helmet Mounted Cueing System (JHMCS) is integrated with existing flat-panel display systems such as the Mobile Modular Display for Advanced Research and Training (M2DART). The degree of blurring that could occur would be dependent upon observers' depth of focus and the extent to which the two displays vary in focal plane distance. In previous research, we investigated whether blurring occurs when two displays are viewed simultaneously at independently varying focal plane distances. These conditions simulated those of a monocular HMD integrated with the M2DART. The results of that research suggested that blurring due to two differing focal planes was not likely to be a significant issue for the current configuration of the M2DART. We present here two additional experiments that extend these earlier results. In the first experiment, luminance levels were decreased, thus increasing pupil size and decreasing depth of focus and the degree of blurring was measured using psychophysical techniques. In the second experiment, blurring and visual discomfort were examined under more typical viewing conditions: observers performed a task similar to off-bore sight targeting in the M2DART using a monocular HMD. They identified the orientation of an aircraft target presented on the M2DART and a test letter presented on the HMD. Assessments of eyestrain and perceived blur were obtained during the performance of this task. The results of these two experiments indicated that depth of focus should not be an issue for standard-resolution displays and, further, that visual discomfort is not likely to be an issue for the integration of a monocular HMD with the M2DART.

ABOUT THE AUTHORS

Marc D. Winterbottom is a Research Psychologist in the Visual Systems Research Laboratory at AFRL, Mesa, AZ. His research focuses on visual perception as it relates to display technologies for simulation and training applications. He has a M.S. degree in Human Factors Psychology from Wright State University and a B.A. degree in Psychology from Purdue University.

Robert Patterson is an Associate Professor in Psychology and the Program for Neuroscience, and a member of the Center for Integrated Biotechnology, at Washington State University. He received a B.A. in Behavioral Science, and a M.A. in Experimental Psychology, from San Jose State University, and a PhD in Experimental Psychology from Vanderbilt University.

Byron J. Pierce is a Senior Research Psychologist at AFRL, Mesa, AZ, where he is Team Lead for the visual research and development program. He was awarded a Ph.D. in Experimental Psychology by Arizona State University, an M.S. in Engineering Psychology by the University of Illinois, and a B.S. in Psychology by Arizona State University.

Christine Covas is an Associate Research Psychologist in the Visual Systems Research Laboratory at AFRL, Mesa, AZ. Her research focuses on visual perception as it relates to display technologies for simulation and training applications. She is in pursuit of a M.S. in Applied Psychology from Arizona State University East and was awarded a B.S. in Applied Psychology from Arizona State University East (2003).

Jennifer Winner is a Student Co-Op with L3 Communications in the Visual Systems Research Laboratory at Air Force Research Laboratory in Mesa, Arizona. She is a graduate student in the Applied Psychology Program at Arizona State University East and was awarded a B.A. in Applied Psychology from Wright State University (2002).

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Christine.Covas@mesa.afmc.af.mil

Jennifer Winner
Link Simulation and Training, Mesa, AZ
Jennifer.Winner@mesa.afmc.af.mil

INTRODUCTION

One important technological development over the last several decades has been the creation of wearable head-mounted visual displays (HMDs) for military and commercial applications (e.g., for review, see Melzer & Moffitt, 1997; Velger, 1998). Despite the potential advantages of HMDs, their use may present one or more technical problems, depending upon the application. For example, when a HMD is worn while simultaneously viewing another synthetic vision display, such as the visual display of a flight simulator (as might occur within an Air Force training environment), both HMD symbology and the simulator environment), both HMD symbology and the simulator imagery must be clearly visible at the same time. For this to occur, both symbology and imagery must be within the user's depth of focus, which refers to the range of distances in image space within which stimuli appear in sharp focus.

In a previous study, Winterbottom, Patterson, Pierce, Covas, and Winner (2005) investigated depth of focus in an environment that simulated a situation in which a monocular HMD was viewed against imagery projected onto a flat panel display (viewed binocularly). These viewing conditions were created to anticipate and examine perceptually related issues with the integration of a monocular HMD, the Joint Helmet Mounted Cueing System (JHMCS), with the Mobile Modular Display for Advanced Research and Training (M2DART), for use during Distributed Mission Operations (DMO) research and training. The M2DART is a 360-degree field-of-view faceted display system consisting of 8 flat panels (see Wight, Best, & Peppler, 1998). Because the screens are flat, viewing distance can vary from 36" to 55" depending on the direction in which the observer is looking.

In the Winterbottom et al. study, the authors optically combined a monocular display (simulating the JHMCS) and a binocular display (simulating the M2DART) and investigated whether significant blurring occurred when the two displays were viewed with differing relative focal distances. Because the monocular display has a fixed focal distance, when an observer views the flat M2DART off-axis (i.e., moves the head to view the corners of the faceted display), the focal distances of the two displays can differ.

The results of the Winterbottom et al. study suggested that images on each display were focused clearly for the current configuration of the M2DART, and thus both displays were within the observers' depth of focus. However, it was shown that for high resolution displays, some blurring can occur. In order to reduce the total amount of perceived blur, the authors recommended that the monocular display be set to a focal distance that is the dioptric average of the distances to the nearest and farthest points on the binocular display system. For the M2DART, the recommended focal distance was 43.5 inches, which represents the dioptric average of the focal distance of the M2DART in the straight ahead view (36") and in the farthest off-axis view (e.g., 55").

In the present study, two experiments were performed that extended the results of the Winterbottom et al. study. In Experiment 1, we investigated the effects of lowering the luminance level of the binocular display on the depth of focus. Lowering luminance level should increase pupil size and therefore decrease depth of focus. This experiment simulated the viewing of a monocular HMD, such as the JHMCS, while binocularly viewing the M2DART. This represented a degraded situation for which observer depth of focus would be expected to be more limited. In this experiment, observers' accommodative state was carefully controlled (e.g., employing brief target exposures). In Experiment 2, we examined perceptual issues attendant with the integration of a monocular HMD with the M2DART under viewing conditions more typical of those for a training exercise. In this experiment, observers performed a dual recognition task and examined whether differences in focal distance between two displays created problems with visual functioning or visual discomfort when a monocular HMD was worn for an extended period of time. In doing so, this experiment simulated the use of a JHMCS for a task such as off-bore sighting (OBS) for a duration similar to a typical mission training session.

EXPERIMENT 1

In this experiment, acuity thresholds and depth of focus were measured under conditions that mimicked an M2DART operating with a relatively low level of display luminance.

Observers

Four observers, all non-pilots, served in this experiment. All observers had normal or corrected-to-normal acuity, and normal binocular vision, color vision, and phoria as determined by the Optec Vision Tester (Stereo Optical Co., Inc., Chicago, IL).

Stimuli and Apparatus

This experiment involved the optical combination of a high-resolution background display viewed binocularly and a high-resolution monocular display. The binocular display was used to simulate the viewing of the multi-faceted front screen of an M2DART, and the monocular display was used to simulate the viewing of a monocular HMD such as the JHMCS. In order to optically combine the two displays, the imagery on the monocular display was directed to the observer's right eye via a beam splitter while he/she viewed the background display with both eyes. The binocular display was positioned in front of the observer and viewed in the straight-ahead position while the monocular display was positioned to the right of the observer and at a right angle to the straight-ahead position.

Two types of stimuli were employed, fixation stimuli and an acuity test letter. The fixation stimuli consisted of a series of five randomly selected consonant letters presented in the middle of the binocular display. The size of each fixation letter was 0.13 deg (stroke width of 1.5 arcmin) at each viewing distance tested (see below). The acuity test letter was a letter 'E' that was presented on either the binocular display or the monocular display. The size of the acuity test letter was varied (i.e., stair-cased, with the smallest possible target letter being 2.5 arcmin) on the monocular display or the binocular display. All stimuli were drawn in a green hue (R, G, B values: 0, 255, 0, respectively) in order to mimic the appearance of JHMCS symbology. The width and height of the letters were approximately equal in terms of the numbers of pixels that defined them (i.e., they appeared as block letters).

To generate the low luminance background on the binocular display, a Barco 909 (Barco, Inc., Xenia, OH) CRT was used to rear-project a 52 x 43 inch image on to a 1.2 gain ProScreen (Proscreen Inc., Medford OR). The Barco 909 is similar to the CRT displays commonly used in the M2DART and was used to present a white background field against which the fixation stimuli and acuity test letter were viewed. The CRT display was capable of projecting approximately 1200 x 1100 resolvable pixels as determined by a standardized measurement procedure (Geri, Winterbottom & Pierce, 2004; see also VESA Flat Panel Display Measurements Standard, Version 2). A PC equipped with a 1 GHz Pentium 4 processor and NVidia GeForce 4 videocard was used to produce the white background that was presented on the Barco 909. A modified Sim 1600 LCoS display (VDC Display Systems, Cape Canaveral, FL) was also used to produce a high resolution inset on the binocular display. The Sim 1600 was capable of projecting approximately 1100 x 800 resolvable pixels (Geri, Winterbottom & Pierce, 2004) under these conditions. With the modification, a pixel size of approximately 0.5 arcmin was achieved. Neutral density filters were used to reduce the luminance so that the black level did not exceed the background luminance level of the CRT projector. The background luminance of the binocular display was 0.11 fL.

To simulate the monocular HMD, a beam splitter was placed in front of the observer's right eye, which directed images to that eye from a second Sim 1600 LCoS projector. The LCoS projector was modified for a short focal length and rear-projected an image 5.5 x 4.4 inches in size onto a small DA-Lite DASS 50 screen (Da-Lite Screen Company, Warsaw, IN). Image size and resolution was similar to that of the LCoS display described above, and neutral density filters were again used to reduce luminance level such that the black level did not exceed the luminance level of the binocular display background field. The luminance of the monocular display with a DAC value of 0 was approximately 0.02 fL. To maintain an equal level of light adaptation in both eyes while viewing the binocular display, a beam splitter was also placed in front of the observer's left eye, which viewed the binocular display without any additional symbology.

A Shuttle PC equipped with a 3 GHz Pentium 4 processor and NVidia GeForce 4 videocard was used to generate the imagery and collect data. The videocard was configured to split a 2048 x 1024 image across the binocular and monocular displays (thus each display presented imagery with 1280x1024 pixels).

The viewing distance from the observer to the monocular display was varied via the operation of a sliding platform upon which the monocular display was positioned. The viewing distance from the observer to the binocular display was varied by manipulating the location of the table at which the observer sat. A chin rest was used to stabilize the observer's head position.

Procedure

We sought to determine whether symbology on the monocular display was within the observer's depth of focus while fixation was maintained on the binocular display. We therefore employed procedures, described below, that were designed to encourage fixation on the binocular display while acuity was measured for the test letter presented on either the binocular or monocular display.

At the beginning of each trial, a set of fixation letters were presented on the binocular display for a duration of 2 sec. During this 2-sec interval, the observer indicated the identity of the centermost letter of the set, which served to ensure that the observer was accommodated to the distance of the binocular display. Following termination of the fixation letters, an inter-stimulus interval of 75 msec ensued, after which the acuity test letter was presented on either the binocular display or the monocular display. The acuity test letter was presented for a duration of 150 msec, which is shorter than the latency of the observer's accommodative response (Campbell & Westheimer, 1960). This short duration prevented the observer from shifting accommodation from one display to the other during the trial. To further discourage observers from shifting fixation away from the binocular display before the trial began, we controlled the observer's expectation as to where the test letter would be exposed by presenting it 70% of the time on the binocular display and 30% of the time on the monocular display. The observer's task was to indicate the orientation of the test letter, which pointed either to the left or right, using a mouse.

To measure acuity thresholds, the size of the test letter was varied according to a staircase procedure, which converged to the 70.7% level (2-down/1-up rule; Levitt, 1971). During each block of trials, two interleaved staircases were used to estimate threshold size for the test letter presented on the binocular display, and two interleaved staircases were used to estimate threshold size on the monocular display. Each observer repeated each block of trials twice, resulting in a total of four threshold estimates for each display type under each experimental condition. Threshold acuity was defined as the smallest size of the gaps in the test letter E that could be discerned based on the average of the four threshold estimates.

The threshold size of the test letter E was measured as the viewing distances to the two displays, monocular and binocular, were independently varied. The viewing distance of the monocular display was either 36” or 43.5”. These distances corresponded to the straight ahead viewing distance in the M2DART and the dioptric average of the nearest and farthest M2DART viewing distances, respectively. The viewing distance of the binocular display could be 28”, 36”, 43.5”, 55”, or 96”. These distances encompassed the range of distances to be encountered in the M2DART and included two additional more extreme distances. The separation distance, in diopters, between the two displays ranged from 0 to +/- 0.5 diopters. The threshold size of the test letter E threshold was expected to increase, indicating increased blur, as separation between the two displays increased.

Results

The results from Experiment 1 are shown in Figure 1. Data represented by the open circles depict threshold size measured on the monocular display for different display separations and a low luminance level for the binocular display. Data shown with filled circles shows results from Winterbottom et al. (2005) where a normal luminance level for the binocular display (i.e., typical of an M2DART) was used. It can be seen that threshold size increased with the dioptric separation between the binocular and monocular displays. Overall, for the dioptric separations tested, all thresholds were smaller than the value of 1.25 arcmin. A similar pattern of results was reported by Winterbottom et al. (filled circles). Data shown by filled squares indicate thresholds measured when the test letter was presented on the binocular display (the horizontal pattern of the data indicates that fixation was maintained on the binocular display). The red dashed line indicates our criterion level for acceptable blurring (corresponding to a 1 arcmin threshold size).

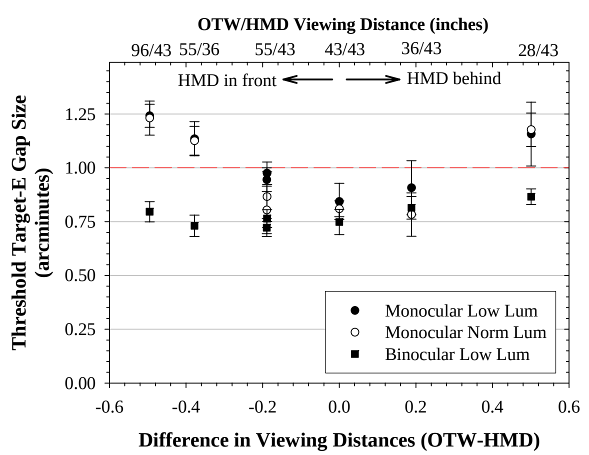

Figure 1. Results of Experiment 1. Threshold size for different relative focal distances and luminance levels.

The data from the present experiment were analyzed by a within-subjects analysis of variance (ANOVA). This analysis revealed that the effect of dioptric separation was significant, $F(2.2, 23.9) = 12.2$, $p < 0.001$. However, there was no significant effect of luminance level nor a significant interaction between separation and luminance level.

Discussion

The results of this experiment indicate that decreasing luminance level from 4 to 0.11 fLdoes not reduce depth of focus shorter than that which occurs with a luminance level typical of the M2DART. Current display technology used in simulation and training generally limits resolution to 2 arcmin/pixel, which is well above the resolution at which effects of depth of focus become noticeable at the range of focal distances measured. Blurring of imagery due to limitations of depth of focus should therefore not be an issue for the integration of a monocular HMD with the M2DART for current resolution displays, even at relatively low luminance levels. However, blurring of imagery could become an issue for high resolution displays (i.e. 1 arcmin/pixel – see Winkler & Surber, 2001). The data obtained in Experiment 1 and in Winterbottom et al, 2005, indicate that the 1 arcmin criterion level can be exceeded at a separation distance of approximately +/- 0.3 diopters. An intermediate focal distance (43.5 inches in the M2DART) for the monocular display is therefore recommended to reduce the total amount of blur as viewing distance changes in a faceted OTW display system.

EXPERIMENT 2

In this experiment, objective measures of visual functioning, as well as subjective measures of eye strain and visual discomfort, were obtained while observers wore a HMD and viewed an actual M2DART. In doing so, the observers performed two recognition tasks, one for a target presented on the M2DART and one for a target presented on either the HMD or on the M2DART. The focal distance of the HMD was 43.5" (0.91 +/- 0.1 diopters), which represented the dioptric average of the focal distance to the M2DART during straight ahead viewing (36") and the farthest off-axis viewing (55"). In this experiment, three viewing conditions were used: a HMD condition, a pseudo-HMD condition, and a No-HMD condition. The pseudo-HMD condition was employed to determine whether any adverse effects were due to simply to wearing an HMD without displayed imagery. This task, although simplified, was intended to be similar to that of off-bore sighting.

Observers

Eight non-pilot observers served in this experiment. All observers had normal or corrected-to-normal acuity, and normal binocular vision, color vision, and phoria as determined by the Optec Vision Tester (Stereo Optical Co., Inc., Chicago, IL).

Stimuli and Apparatus

In the HMD condition, observers wore a monocular HMD. The display device was a monochrome LCD-based display provided by Rockwell Collins/Kaiser Electro-Optics, Carlsbad, CA (one half of a Kaiser ProView XL 40). A visor was attached to the helmet in order to equalize the luminance transmitted to each eye (the transmittance of visor and HMD were both 25%) while viewing an out-the-window scene presented on the M2DART.

Two types of stimuli were employed. One stimulus was displayed on the M2DART and consisted of a simulated image of an F-16 aircraft whose nose was pointing either rightward or leftward on each trial. The F-16 was seen against a static terrain database depicting a scene of the National Training Center, near Bicycle Lake in California. The other stimulus was displayed on either the M2DART or the HMD and consisted of a test letter "E" whose orientation was either rightward or leftward. The test letter was drawn with a green hue as in Experiment 1. The HMD and background imagery are shown in Figure 2.

Figure 2. Apparatus used in Experiment 2.

When the target letter E was displayed on the HMD, it appeared along with a static image of symbology similar to that shown on the JHMCS. The JHMCS symbology was visible throughout the task (HMD condition only – see Figure 3).

The terrain imagery was generated using commercial database development software (World Perfect 2.0, MetaVR Inc., Brookline, MA). The terrain imagery was displayed on three channels of an M2DART, using full-color CRT projectors (Barco, Inc., Model 808).

The imagery subtended 240 deg (horizontal) × 63 deg (vertical) at a viewing distance of 36" in the straight ahead view. Each display channel provided 1280 x 1024 pixels, at an update rate of 60 Hz. A joystick, interfaced to a PC, was used by the observer to initiate each trial and to indicate aircraft orientation and test letter orientation.

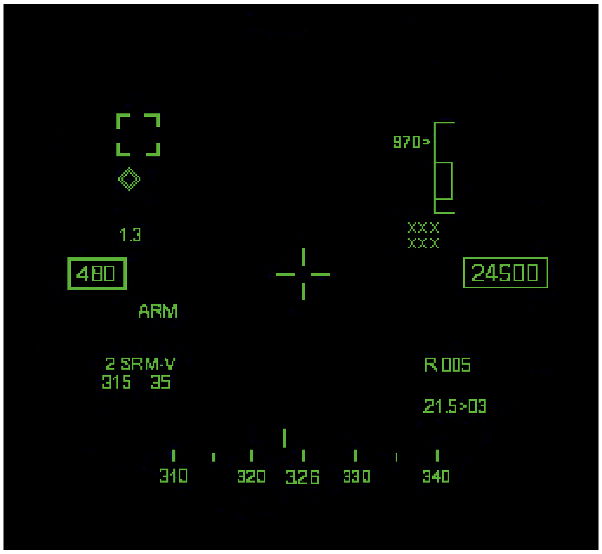

Figure 3. Symbology visible in monocular HMD.

A set of nine objective vision tests were administered to each observer, which was composed of the following: (1) left eye near acuity, (2) right eye near acuity, (3) both eyes near acuity, (4) left eye far acuity, (5) right eye far acuity, (6) both eyes far acuity, (7) lateral phoria (8) Prince Rule (measuring accommodative amplitude), and (9) flip lens (measuring accommodation latency, which has been shown by Kooi, 1997, to be sensitive to eyestrain resulting from the viewing of visual displays).

A set of surveys were also administered to each observer. These surveys contained a total of 12 items that asked the subject about several topics, namely eye strain (5 items), fatigue (4 items), and physiological discomfort (3 items). This survey was similar to a survey developed by Ames, Wolffsohn, & McBrien (2005).

Procedure

The design of this experiment was composed of three conditions. In the HMD condition, the observer wore the HMD and viewed the M2DART through the semi-transparent visor. Here, the F-16 was presented on the M2DART and viewed binocularly, and immediately following that presentation the test letter "E" was exposed on the HMD (embedded within the static symbology similar to that used in the JHMCS-see Figure 2) which was seen only by the right eye (both the F-16 and test letter would appear in approximately the same visual direction if the observer did not move his or her head following the presentation of the F-16). In this condition the observer had to view both the M2DART and the monocular HMD.

In the pseudo-HMD condition, the observer again wore the HMD and viewed the M2DART through the semi-transparent visor. In this case, however, both the F-16 and the test letter were presented sequentially on the M2DART in the same location. In this condition the observer needed only to view the M2DART, but under the same viewing environment as the HMD condition.

In the no-HMD condition, the observer did not wear the HMD while viewing the M2DART. Here, both the F-16 and test letter were presented sequentially on the M2DART in the same location. This condition eliminated the restricted field of view, lower contrast level, lower luminance, and additional weight that accompany the wearing of a HMD.

At the beginning of each trial, a brightly colored circle (the “beach ball”, diameter = 3.5 cm; luminance = 12.8 fL.) appeared on the M2DART which indicated the location of the F-16 (and in the pseudo-HMD and control conditions, the test letter as well). The F-16 (and test letter in the pseudo-HMD and control conditions) could appear in one of five locations on the M2DART: upper left, upper right, middle left, middle right, or center location. The F-16 target could thus appear on any of the front 3 screens of the M2DART. The viewing distance to the F-16 target therefore ranged from approximately 36” (center) to approximately 50” (upper corners).

Once the observer located the beach ball, he/she initiated the trial by depressing a button on the joystick. The beach ball was then replaced by the F-16 whose nose was pointing either rightward or leftward (see Figure 4). The starting distance of the F-16 was 500 meters (1640 ft), and it was presented for a duration of three seconds. The F-16 moved in a small circle (rate of movement = 120 degrees/sec). The observer's task was to indicate the direction of the nose of the F-16 by depressing a second response button on the joystick. After the observer indicated his or her response, the test letter "E" was immediately presented on either the HMD (experimental condition) or the M2DART (pseudo-HMD and no-HMD conditions) with its orientation being either rightward or leftward. The size of the E was approximately 0.7 degrees on the M2DART and approximately 0.3 degrees on the HMD. The observer's task was to indicate the orientation of the test letter by depressing a third button on the joystick.

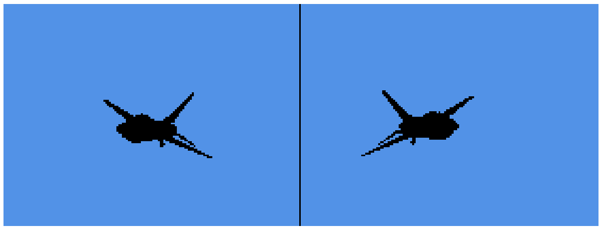

Figure 4. F-16 model used in Experiment 2.

Over trials, both the distance of the F-16 and the duration of the test letter "E" were individually stair-cased using the 2-down/1-up rule, with each staircase converging to the 70.7% level of performance.

At the beginning of each experimental session, the set of nine objective vision tests and the survey were administered to each observer (pre-test). Next, the observer performed a number of trials (on average approximately 100) on the dual recognition tasks described above for a duration of 25 minutes, after which the set of vision tests and surveys were again administered (mid-test). Finally, the observer again performed a set of trials on the dual task for a duration of 25 minutes, after which the vision tests and survey were last administered (post-test).

It is expected that, if wearing the HMD decreases visibility for any reason (such as blur due to depth of focus limitation or binocular rivalry), that performance will decrease for the HMD condition relative to the pseudo-HMD or no-HMD conditions. Furthermore, if observers experience any eyestrain, fatigue, or discomfort, these symptoms would be expected to be reflected in the objective vision test results and/or the subjective questionnaire results (post-test scores will differ from pre-test scores).

Results

Figure 5 depicts the distance thresholds for identifying the orientation of the F-16 for the five M2DART display locations and three experimental conditions. The figure shows that, overall, performance was best when the F-16 was presented in the center of the display and declined as the F-16 was presented in the corners of the display. Moreover, the figure also shows that performance was best in the no HMD condition, intermediate in the pseudo-HMD condition, and worst in the HMD condition. Overall, the decline in performance under the HMD condition relative to the no-HMD condition was fairly uniform across display locations, and amounted to a reduction in performance of about 33%.

These data were analyzed using a within-subjects ANOVA, which revealed that the effect of target location was significant, $F(1.7, 11.8) = 22.6$, $p < 0.001$, as was the effect of HMD condition, $F(1.9, 13.1) = 32.2$, $p < 0.001$.

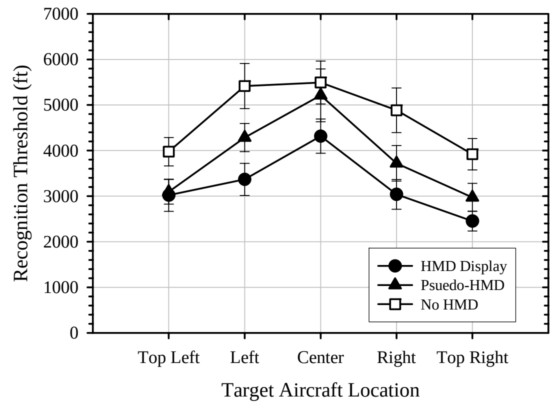

Figure 5. Experiment 2. F-16 recognition thresholds for different display locations and viewing conditions.

Figure 6 depicts the duration thresholds involving the test letter "E" for the five M2DART display locations and three experimental conditions. The figure reveals that performance was best for the no-HMD condition. Performance for this condition is consistent across target location. Different trends occurred for the Pseudo-HMD and HMD conditions. The test letter E duration thresholds are generally higher for the HMD condition relative to the no-HMD condition for these conditions. In particular, threshold duration increased by approximately 29% for the center target location under the HMD condition.

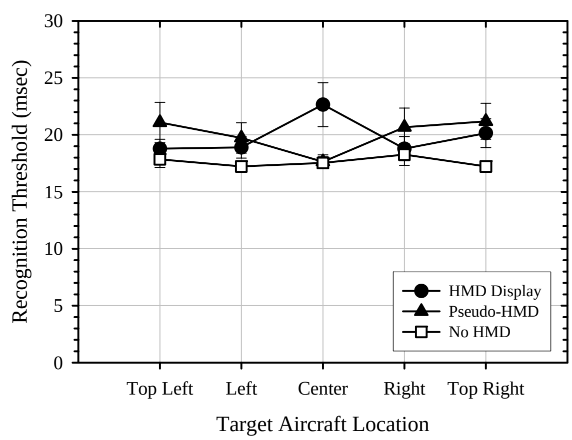

Figure 6. Experiment 2. Test letter E duration thresholds for different display locations and viewing conditions.

These data were analyzed using a within-subjects ANOVA, which revealed that the effect of viewing condition was significant, $F(1.7, 11.6) = 7.2$, $p < 0.05$, as was the interaction between viewing condition and location, $F(4.2, 29.6) = 4.5$, $p < 0.01$.

With respect to the objective vision tests, there was no significant change in any of the measures across the experimental sessions (i.e., from pre-test to mid-test to post-test). With regard to the survey, there was no significant change in reported eye strain, fatigue, or physiological discomfort across the experimental sessions.

Discussion

These results show that, overall, observers' ability to recognize the orientation, or aspect, of the F-16 declined when wearing the HMD. However, their ability to obtain information from the monocular HMD (i.e., identifying the orientation of the test letter E), which simulated the JHMCS, was very fast. On average, observers were able to identify the test letter when it was exposed for less than 22 msec. However, thresholds increased when observers attempted to identify the test letter E after identifying the orientation of the F-16 when presented in the center location on the front screen in the HMD condition. For this location, test letter duration thresholds were several milliseconds greater than that found for the other locations. The most likely cause of this increase is that the visibility of the test letter, when presented on the HMD, decreased when viewed against the brightest portion of the M2DART screen (the "hotspot" typical of wide field-of-view rear-projection displays).

The decrease in threshold distance for recognizing the F-16 under the pseudo-HMD condition, relative to the No-HMD condition, can be attributed to the decreased luminance and contrast caused by viewing the OTW scene through a 25% transmittance visor and monocular HMD display. However, there was a further decrease in performance for the HMD condition, with the only difference being that symbology was now presented on the HMD. Although the symbology and LCD black level on the HMD were very dim, it is possible that this further reduction in visibility in the right eye could account, or partially account, for the greater reduction in performance on the F-16 recognition task. Alternative explanations include the necessity to alternate attention between the two displays, or the presence of binocular rivalry.

Importantly, there was no indication of eyestrain based on the objective eye tests we conducted for this experiment. After nearly an hour performing these simulated off-bore sighting and recognition tasks, measures of acuity, accommodative amplitude, and accommodative latency were not shown to be any different compared to the same tests prior to beginning the tasks. Additionally, subjective measures failed to indicate any increase in visual discomfort or perceived blurring of imagery over the course of these one hour tasks.

GENERAL DISCUSSION

The purpose of this study was to determine whether depth of focus and continuous viewing of displays at differing focal distances would present an issue for the integration of the JHMCS with the M2DART for purposes of DMO simulation and training. The results of Experiment 1 showed that, when a monocular display is integrated with a binocular display, perceived blurring of imagery due to limitations in depth of focus is not likely to be an issue even under conditions of relatively low luminance. For a 1-arcmin criterion, however, depth of focus can be exceeded for an approximately +/- 0.3 diopter separation between the two displays. This implies that some perceived blurring could occur for simultaneous viewing of high resolution displays. To reduce the possibility of blurring over the range of distances likely to be encountered in the M2DART, an intermediate focal distance of 43.5 inches was therefore recommended for the monocular display.

Experiment 2 was undertaken to examine objective performance and subjective eyestrain under conditions in which the observer was free to adjust accommodative state over the course of a one-hour simplified off-bore sighting and letter recognition task. Importantly, neither objective eye tests nor subjective assessment by our observers indicated the presence of significant eyestrain or discomfort as a result of wearing the HMD while performing the two tasks. Some decline in recognizing the orientation of the aircraft when wearing the HMD was noted; however, much of this decline can be attributed to the presence of a tinted visor which reduced visibility of the OTW scene. This potential hindrance to target recognition and identification should be significantly reduced with the actual JHMCS since the visor transmittance is considerably greater than we tested here.

In Experiment 2, there was also some indication that the use of the monocular HMD impaired performance relative to when observers did not wear the HMD, or when the HMD was worn but no information was displayed. Because it was shown in Experiment 1 that depth of focus should not be an issue for displays with pixel sizes greater than about 1.25 arcmin, issues related to accommodation would likely not be the cause of this impairment. Rather, this impairment with the HMD may be due to a number of other factors.

First, viewing the M2DART with both eyes and the HMD symbology with one eye may provoke the condition of visual suppression called binocular rivalry.

The presence of rivalry could have impaired performance on the F-16 recognition task.

Second, in the HMD condition, due to the presence of the HMD symbology, observers may have relied more heavily on their left eye to view the F-16 target relative to the pseudo-HMD and no-HMD conditions. Thus comparisons of performance across the two displays could be confounded by the number of eyes used for the task. In particular, binocular thresholds are typically better than monocular thresholds by a factor of about 1.41 (two sensors are more likely than one to detect a signal, typically by a factor of $\sqrt{2}$, or 1.41). Identification of aircraft orientation in the HMD condition might therefore be expected to decline a small amount.

Third, and perhaps most interesting, performing the aircraft recognition task on the HMD required visual attention to be shifted from one display surface, the M2DART, to another display surface, the HMD, to perform the second task. Anticipation of this attentional switch may have affected the performance of the aircraft recognition task.

In conclusion, depth of focus and visual discomfort do not appear to present significant issues for the integration of a monocular HMD with the M2DART for simulation and training purposes. However, additional research should be conducted to examine whether increased latencies for target identification or for recognition of HMD presented symbology can be expected under conditions where two displays are viewed simultaneously in a DMO training environment.

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REFERENCES

Ames, S., Wolffsohn, J., & McBrien, N. (2005). The development of a symptom questionnaire assessing virtual reality viewing using a head-mounted display. *Optometry and Vision Science, 82 (3), pp. 168-176.*

Campbell, F. & Westheimer, G. (1960). Dynamics of the accommodation responses of the human eye. *Journal of Physiology, 151, pp. 285-295.*

Geri, G., Winterbottom, M., Pierce, B. (2004). Evaluating the spatial resolution of flight simulator visual displays. *Air Force Research Laboratory Technical Report Number: AFRL-HE-AZ-TR-2004-0078*.

Kooi, F. (1997). Visual strain: a comparison of monitors and head-mounted displays. *Proceedings of SPIE: Imaging Sciences and Display Technologies, 2949, pp. 162-171.*

Melzer, J. E. & Moffitt, K. (1997). *HMD design--putting the user first.* In J.E. Melzer & K. Moffitt (Eds.), Head mounted displays: Designing for the user. N.Y.: McGraw-Hill.

VESA Flat Panel Display Measurements Standard, Version 2, Video Electronics Standards Association, Milpitas, CA, June 2001, pp.76-77.

Levitt, H. (1971) Transformed up-down methods in psychoacoustics. The *Journal of the Acoustical Society of America, 49, 2, pp. 467 – 477*.

Velger, M. (1998). *Helmet-mounted displays and sights.* Boston, MA: Artech House.

Wight, D. R., Best, L. G., & Peppler, P. W. (1998). M2DART: A Real-Image Simulator Visual Display System. *Air Force Research Laboratory Technical Report Number: AFRL-HE-AZ-TR-1998-0097*.

Winkler, B. & Surber, B. (2001). Seeing Clearly – The Emergence of Ultra High Resolution Displays. *In 2001 Interservice/Industry Training, Simulation and Education Conference (I/ITSEC) Proceedings. Orlando, FL: National Security Industrial Association.*

Winterbottom, M., Patterson, R., Pierce, J., Covas, C., & Winner, J. (2005). The influence of depth of focus on visibility of monocular head-mounted display symbology in simulation and training applications. *Proceedings of the SPIE: Helmet- and Head-Mounted DisplaysX, 5800, pp. 65-73.*