

## Vergence Mismatch Effects in a Binocular See-through HMD

**Michael P. Browne**  
SA Photonics  
San Francisco, CA  
[m.browne@saphotonics.com](mailto:m.browne@saphotonics.com)

**Kirk Moffitt**  
Human Factors Consultant  
La Quinta, CA  
[kirkmoffitt@earthlink.net](mailto:kirkmoffitt@earthlink.net)

**Marc Winterbottom**  
USAF/HEAE  
Mesa, AZ  
[Marc.winterbottom@mesa.afmc.af.mil](mailto:Marc.winterbottom@mesa.afmc.af.mil)

### ABSTRACT

Portable faceted simulator systems are relatively easily deployable to numerous locations around the globe. Although these uncollimated, faceted displays allow for a relatively small footprint, the viewing distance for faceted simulator screens can vary significantly as a user moves their head and direction of gaze. When binocular head mounted displays (HMDs) are used in tiled simulators to overlay symbology, the difference between the focus and vergence of the HMD and the out-the-window view can cause human factors issues. These issues can manifest themselves as blurred imagery, doubled imagery or eyestrain. These effects are not normally observed in flight, where the pilot's "real world" is at or near optical infinity.

We performed preliminary experiments in a faceted simulator using a number of different display conditions for overlaid symbology: on-screen, monocular HMD and binocular HMD. The HMD conditions were tested with a range of image distances from 36 to 55 inches, which represent the range of viewing distances in a faceted display system used by the Air Force (M2DART). Subjects were queried for apparent distance of the overlaid symbology, blurriness of symbology, presence of doubled imagery and viewing comfort.

The preliminary results showed no obvious blurring of the imagery due to focus mismatch, but large effects due to vergence mismatch. These effects included symbology which appeared to "float" in front of or behind the out-the-window view, doubling of the imagery or symbology, and uncomfortable viewing of the overlaid symbology and imagery. No single binocular symbology convergence setting prevented reports of double vision, apparent distance effects and/or viewing discomfort. Monocular symbology alleviated the vergence mismatch, but was judged less comfortable to view. These results indicate that for the M2DART, and other faceted simulators with similar viewing distances, some method of vergence mismatch mitigation is required to permit the integration of binocular HMDs for training applications.

### ABOUT THE AUTHORS

**Michael Browne** is the Vice President of Product Development at SA Photonics in San Francisco, California. He has a Ph.D. in Optical Engineering from the University of Arizona's Optical Sciences Center. Mike has been involved in the design, test and measurement of head mounted display systems since 1991. At Kaiser Electronics, Mike led the design of numerous head mounted display and rear-projection display systems, including those for the F-35 Joint Strike Fighter. Mike leads SA Photonics' efforts in the design and development of person-mounted information systems, including body-worn electronics, head-mounted displays and night vision systems.

**Kirk Moffitt** is a human factors consultant specializing in real and virtual displays and controls. He holds a Ph.D. in Engineering Psychology, and has 27 years of industry experience. He is the co-editor of the McGraw-Hill text *Head Mounted Displays: Designing for the User*. His clients have included military, medical, industrial and entertainment companies. Dr. Moffitt has also taught courses in human factors and statistics for the University of Southern California, and seminars on HMD design for SPIE and other organizations.

**Marc 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.

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**Marc Winterbottom**  
USAF/HEAE  
Mesa, AZ  
[Marc.winterbottom@mesa.afmc.af.mil](mailto:Marc.winterbottom@mesa.afmc.af.mil)

### INTRODUCTION

Flight simulation has always been a critical component of aviation. While early flight simulators had no visual display, this capability is now considered essential for many applications. Simulator displays have continued to improve over the past 70 years, from the very early shadowgraphs and projected film loops to the modern day large projection domes. A major problem with these displays is that as more situation awareness is desired, the larger the footprint of the display system and the harder it is to deploy these systems to other training locations around the globe.

The M2DART (Mobile Modular Display for Advanced Research and Training) was developed to provide a more portable simulator system that could be reconfigured and deployed for a variety of training tasks around the globe (Wight, Best & Pepler, 1998), yet still provide a 360° wrap-around field of view to permit maximum training capability. A key to making this a portable system is the use of rear projection displays at a viewing distance as close as 36". This viewing distance is much closer than the optical infinity found in the real world or the 6-feet or greater found in large dome simulators. In addition, the use of screen facets means that there is a range of screen distances to contend with—extending from 36" to 55" in the M2DART. Further, since the development of the M2DART, a variety of manufacturers have developed similar faceted display designs (e.g. Boeing VIDS, L3 Simusphere, Glass Mountain Optics WASP). These display systems are used widely across the services for a variety of training applications.

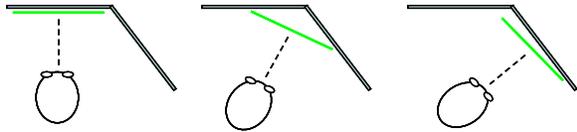
Many current (and almost all future) fighter jets will have a head mounted display (HMD) as part of the visual cueing system in the cockpit. For maximum reality, many simulators have HMDs in them. In addition, the Joint Strike Fighter will be the first US fighter jet with a binocular HMD, which will serve as

the primary flight instrument. For training applications, the integration of a binocular HMD brings additional concerns for vergence mismatch, as outlined below.

Current binocular HMDs have fixed-convergence optics, which means that the two optical systems (one for each eye) converge to a single distance, unlike our normal vision, which constantly adjusts vergence as we shift our attention from near objects to far ones. This means that a user with an HMD will always have vergence mismatch when the scene distance is different than the distance at which the HMD is converged.

Focus may be either fixed or adjustable, but even adjustable focus systems are set to a single distance for a given user/configuration. This means that as the operator looks to different positions in a faceted display system (e.g. the M2DART), there will be a difference in focus distance between the simulated out-the-window imagery and the HMD imagery.

Using a standard binocular HMD (one without automatic focus and vergence adjustment) ensures that there will be focus errors and binocular disparity in the M2DART. This is depicted in Figure 1, where two of the M2DART's eight screens are shown in a top-down view. The left panel shows the pilot pointing his head straight-ahead where the plane of virtual symbology (shown in green) is coplanar with the simulator screen. The center panel shows the pilot pointing his head at the vertex of the front and side screens, where a noticeable discrepancy in some of the distances between locations on the virtual symbology plane and the simulator screens can be seen. The right panel shows the head orientation as not quite orthogonal to the display screen, resulting in the virtual symbology image plane being slanted relative to the side screen. This case also shows a varying distance between the plane of the symbology and the simulator display screen.



**Figure 1 Simplified overhead view showing the mismatch between the HMD image plane (shown in green) and two adjoining faceted screens of a faceted display system.**

Although research has shown that focus differences are not a noticeable issue in a well-designed monocular see-through HMD used in the M2DART (Winterbottom, Patterson, Pierce, Covas & Winner, 2005), the JSF HMD is a binocular display that has the potential for creating unwanted depth effects due to binocular disparity (i.e. the difference in vergence between the symbology and the display screen). Small amounts of disparity may be seen as symbology which appears to float in front of the simulator screen or is buried behind the screen. Larger amounts of disparity may be seen as blurred or doubled/diplopic imagery. [This situation can be easily demonstrated by focusing on a distant object while holding up a finger in your line of sight. If you maintain focus on the distant object, you will notice that your finger appears doubled.] In addition, there may be latent vision issues that lead to eyestrain, headaches or work impairment, which would reduce pilot motivation to complete missions in the simulator.

This report summarizes the results of an investigation of imaging and display conflicts that may occur when using a binocular helmet-mounted display (HMD) in a faceted flight simulator. The specific systems of interest are the JSF HMD and the M2DART, although the findings will also have implications for other similar faceted display systems using binocular HMDs. The major imaging and display conflicts that we have identified are between the focus and convergence of the HMD symbology, and the distance of the simulator image. Since the HMD projects a flat image, this plane can cut across the angled screens found in a faceted simulator. These conflicts are capable of creating viewing discomfort, double images, blur and odd distance perceptions.

The human accommodation and vergence response is a complex system that allows us to direct our attention at a given object in our visual field. Accommodation brings an object into focus and drives the vergence of the eyes. Vergence brings an object into single vision and drives the accommodation response. This crosslink of vergence and accommodation facilitates the direction of attention. The object of our attention is almost always seen as a single and in-focus image. The

appearance of an object that is diplopic or doubled, or that is blurry, is disconcerting to the observer.

In the real world, the focus and vergence of objects are in correspondence well enough to prevent blur or double vision. Implementing dynamic focus and vergence in a binocular HMD would be an extremely expensive and complicated endeavor. This is why all existing HMDs have a fixed vergence angle and an optical focus that is either fixed or manually adjusted. One concern with binocular HMDs (shared by other binocular displays) is that displayed objects can be horizontally shifted to induce stereo depth. This dissociation between vergence and focus can lead to eyestrain and fatigue. With see-through HMDs, an additional problem is the vergence and focus of HMD graphics and an optical mismatch with the outside scene.

The M2DART uses eight flat projection screens arranged to create an approximately 360° (H) x 100° (V) immersive simulation environment. When the HMD-wearing pilot positions his head straight ahead, the orientation of his helmet mounted display is orthogonal with the projection screen. In this case the virtual HMD imagery lies on a plane parallel to the screen. The vergence of the HMD binocular imagery determines the perceived distance between the HMD's virtual image and the M2DART screen real image. Convergence of the HMD imagery relative to the simulator screen results in the symbology *floating* in front of the simulator scenery. Divergence relative to the screen should place the symbology *behind* or *buried* in the scenery—though this creates an impossible and confusing image.

When the pilot rotates his head from this straight-ahead position, the virtual imagery is no longer parallel to the front screen. The result is horizontal binocular disparity between the screen and HMD image. Several arc-minutes of binocular disparity creates a compelling sense of depth with imagery remaining single. Larger amounts of disparity can result in one of the images appearing diplopic or double. The maximum 20-inch difference in distance (or depth) between the HMD and screen image in the M2DART exceeds the commonly cited threshold for double vision of 8.8 minutes for image convergence with a distant real-world scene (Warren, Genco & Connon, 1984) by a large factor.

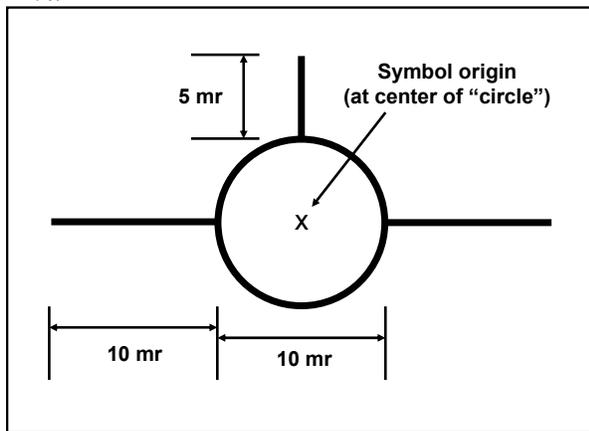
## METHODS AND APPARATUS

### Apparatus

The Rockwell Collins ProView XL40STm HMD was chosen for this study. This HMD has independent L/R

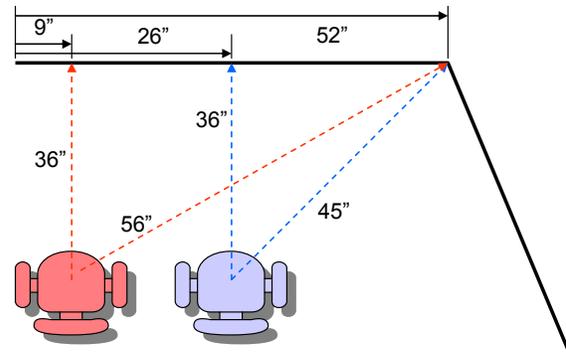
channels, and supports a 1024x768 pixel image. Each channel of the HMD was driven by a laptop PC. The focus of the Rockwell HMD was measured by a dioptometer to be between 0.4 and 0.5 diopter. This range captures the value given by Rockwell of 0.42 diopters. The most optimistic (i.e., closest) focus measure of 0.5 diopter corresponds to a distance of 79". This focus distance is significantly greater than the focus distances in the M2DART (36-55 inches), but was deemed acceptable for this initial investigation.

An aiming symbol, shown in Figure 2, was constructed with a diameter of 34 minutes (10 mr) and a thickness of 2 pixels, or 4.2 minutes (1.2 mr). The luminance of the HMD was 15 fL and the symbology was monochrome green. The see-through transmission was 21%.



**Figure 2. HMD symbology**

Two rear-projection displays were used to emulate the front and right-side screens of the M2DART faceted simulator. The Sony SXRD 3-panel reflective LCOS monitors were modified to minimize the size of the bezel. The horizontal extent of each monitor was 52". These monitors were positioned on stands and abutted at an angle of 122.5°. The seated subject was positioned either centered with the front display or positioned 9" in from the left edge of the display (see Figure 3). The center position placed the subject at a viewing distance of 36" to the center of the front screen, 45" to the vertex of the two screens and 36" from the center of the side screen when the head was turned. From the side position, the viewing distance was 36" straight ahead and 55" to the vertex of the two screens.



**Figure 3. Seating positions and associated viewing distances**

A desktop PC was used to display 1920 x 1080 pixel images on each monitor. A panoramic desert scene, shown in Figure 4, was displayed on the two screens. The *naked-eye* luminance of the scene was approximately 100 fL in the center (for the brightest part of the screen), 86 fL ahead of the left-chair position, and around 30 fL near the vertex of the two monitors (for both chair positions). The transmission through the HMD is 21%, so that to the eye, the background scene luminance as viewed through the HMD ranged from 21 fL to around 6 fL. For the on-screen condition, the green flight symbol was displayed at several locations directly on the screen. A subject in front of the two monitors is shown in Figure 5.



**Figure 4. Panoramic desert scene**



**Figure 5. Subject positioned in front of the two monitors**

## General Method

The chair was first positioned centered with the front monitor, with the viewing distance (eye pupil to screen) set to 36" and verified using a yardstick. This positioning resulted in a viewing distance of 45" to the vertex of the monitors and 36" to the middle of the right monitor when the subject rotated and translated their head and body toward this monitor (see Figure 3). The HMD was first set to display right-eye only monocular symbology. Subjects were instructed to look straight ahead and indicate whether the symbol or background appeared blurry or double, the distance of the symbol relative to the background (further, same, closer, much closer), and their viewing comfort (comfortable, somewhat uncomfortable, very uncomfortable). This sequence was repeated while looking near the vertex and at the center of the right monitor. Next, the symbology was changed to binocularly viewed at convergence distances of 36 and 45 inches. A final condition at the 36" viewing distance was an on-screen symbol that was viewed without the HMD.

The chair was then shifted so that the subject was 9" from the left edge of the front monitor, keeping the subject distance at 36" from the front monitor when looking forward, and increasing the distance to the vertex to 56". The symbology convergence was set to 36" and 56" for the two test conditions—corresponding to the distance to the front screen and the vertex (see Figure 3).

## Subjects

Visual acuity was measured for the left and right eyes using a 20' wall chart. The criterion for participation was 20/30 in each eye. Interpupillary-distance (IPD) was measured with a ruler. Eye relief was set by the subject to a comfortable distance.

Double vision or diplopia was explained to the subject by having them hold up a finger at arm's length, and switching attention between their finger and a distant object. Binocular balance was verified using the HMD to display an image consisting of a textured ball shown in the left-eye only, a binocularly viewed ball, and right-eye viewed ball. Balance was indicated by the report of three balls vertically aligned. This test was needed to exclude subjects with deficient binocular vision.

The HMD vergence was visually calibrated for an IPD of approximately 62 mm. The IPDs for the six subjects are provided in Table 1. Given a fixed vergence angle for imagery, a narrow-IPD individual will see the

imagery as closer while the wide-IPD individual will see the imagery as further. All subjects except for MC had previous familiarity with HMD imagery.

**Table 1. Subject IPDs**

<u>Subject</u>	<u>IPD (mm)</u>
MW	60
GG	70
MC	65
MB	63
KM	62
TE	57

## RESULTS

### On-Screen Symbology

The green symbol was displayed on the screen at three positions—the middle of the forward screen, at the right edge of the forward screen near the vertex, and the middle of the side screen. Subjects simply observed the three symbols and responded to questions regarding blur, double imagery, apparent distance, and viewing comfort. The HMD was not worn. Responses were the same for each symbol position.

The on-screen symbol had no binocular-disparity with the scenic background imagery and exhibited no double imagery for any of the subjects. Viewing of the symbol was rated "comfortable" by all subjects.

On-screen graphics are sometimes seen as "closer" than the background, and this was reported by Subject MC. This can be attributed to the symbol being an opaque luminous green object that is not integral to the scene (i.e. the symbol occludes the scene, which normally indicates that the object is closer in distance).

### Monocular Symbology

In this condition, the green symbol was displayed on the HMD to the right eye only. This eliminates binocular disparity between the symbol and the screen image.

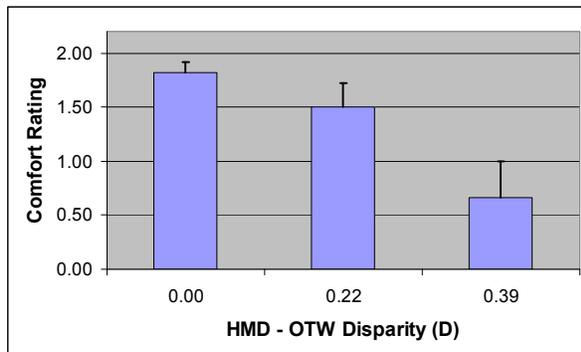
The absence of binocular disparity with the monocular symbol precludes the symbol from being seen as double. This was confirmed at each symbol location. The symbol appeared closer than the background for all subjects. Although there are no binocular disparity cues to depth, the monocular distance cues all indicate that it is closer than the background.

Reports of viewing discomfort by GG, MB, KM and MC can be attributed to binocular rivalry. The competition between the scenic background and the monocular symbol was explicitly noted by several subjects.

### Binocular Symbology

A variety of combinations of viewing distance (36", 45", and 55"), and HMD vergence settings (36", and 45") were used for the binocular symbology viewing condition. To simplify explanation of the results, the responses of the 6 subjects have been averaged and are summarized in Figures 6, 7, and 8.

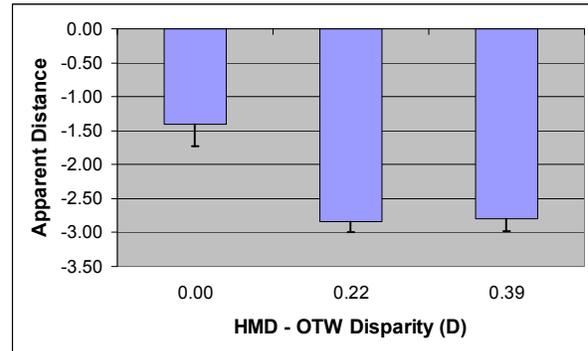
Figure 6 gives a graphical summary of the rated comfort versus disparity, where disparity is expressed in diopters or  $m^{-1}$ . The comfort scale was assigned such that 2 is comfortable, 1 is uncomfortable and 0 is very uncomfortable. As can be seen from the graph, as the vergence mismatch increases, comfort decreases. Although average comfort ratings clearly decrease as vergence mismatch increases, individual subject responses varied considerably. Subject MC, for example, rated the 36" viewing condition/36" vergence condition as uncomfortable to view while all other subjects rated the same condition as comfortable to view.



**Figure 6. Comfort vs. Disparity, expressed in Diopters (D). Increasing disparity leads to reduced comfort (2 = comfortable, 1 = somewhat uncomfortable, 0 = very uncomfortable)**

Figure 7 is a plot of the apparent symbology distance compared to the disparity. Although the distances were reported to be the same for both non-zero disparities, it is obvious that when there is zero disparity, the distance difference is minimized. Individual responses again varied considerably for perceived distance. Subject MC, for example, indicated that the perceived symbology distance was behind the desert scene for the 36" viewing condition/36" vergence condition while most other subjects indicated that the distance between

the symbology and desert scene were approximately the same for that condition.



**Figure 7. Apparent Distance vs. Disparity, expressed in Diopters (D). As disparity increases, the distance appears closer. (0 = same distance, -1 = somewhat closer, -2 = closer, -3 = much closer)**

### DIPLOPIA THRESHOLDS

In order to better assess the relationship of HMD vergence and monitor viewing distance, we conducted a preliminary test to estimate the diplopia threshold.

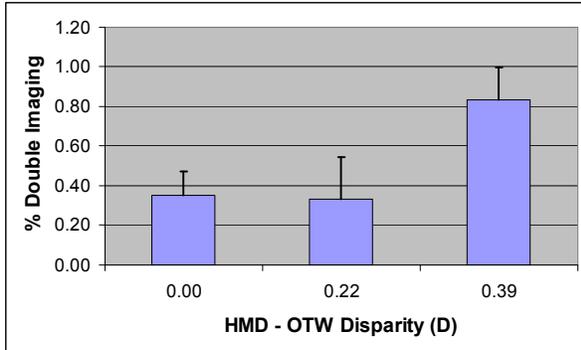
#### Methods

Subjects were seated in the side position and 36" from the front monitor. Subjects were asked to sequentially look at increasing distances to the front monitor using small dots at the bottom of the monitor as guides. At each position, the subject would indicate whether the symbol appeared single or double. This scanning sequence was repeated five times. The same six subjects participated in this second experiment.

#### Results

Each subject adopted a slightly different criterion for double images. The median distance for diplopia between 41.0" and 43.5" corresponds to a binocular disparity of 38 minutes.

The percent of subjects seeing double images is plotted against the disparity in Figure 8. As shown, there is little difference in reported diplopia between 0 and 0.22 diopters. For a disparity of 0.39 diopters however, nearly all observers reported diplopia.



**Figure 8. Percent of Subjects Seeing Double Images as a Function of Disparity**

## DISCUSSION

Three methods of simulating HMD symbology in a training environment were examined in this preliminary study: on-screen symbology, monocular HMD symbology, and binocular HMD symbology. The purpose of this research was to anticipate potential human factors issues that may be associated with developing a training system for the JSF and similar aircraft that are expected to use a binocular HMD as the primary flight instrument. As expected, the on-screen symbology resulted in the fewest reports of discomfort, diplopia, and mismatch in apparent distance. Thus this method may provide a relatively low-cost method for simulating binocular HMD imagery in a training system while avoiding some perceptual issues. An obvious drawback to this approach however, is that it is not representative of pilots' experience with the HMD in the aircraft and the appearance of HMD symbology and other imagery against the out-the-window scenery will be much different (e.g. contrast, transparency, visibility, color, etc.). Similarly, although the monocular HMD condition also reduced reports of discomfort, diplopia, and disparity in apparent distance, and would likely cost less than a binocular HMD, the experience of the pilot in the training system would again be significantly different than with a binocular HMD in the aircraft. Binocular rivalry issues, and hence issues with the visibility of symbology could be introduced. Also, the visibility of symbology when the pilot looked over his shoulder at a potential target would be different because the HMD imagery only appears in one eye.

A binocular HMD integrated with a real-image rear-projected display system would provide a training experience most similar to that of the real aircraft, however the results of the present study show that issues with discomfort, disparity in apparent distance,

and diplopia may be introduced, particularly for faceted display systems where there is significant variation in viewing distance based on direction of gaze. Based on these preliminary results, nearly all observers reported significant discomfort and diplopia for a vergence disparity of 0.39 D (e.g. the maximum change in distance for the M2DART facets).

One potential problem with this investigation of binocular HMD use in the M2DART faceted flight simulator was the focus distance of the HMD. The  $\sim 0.5$  diopter, or 79", focus distance was further than the 36" to 56" screen distances that were studied. Possible outcomes of this distant HMD focus include: 1) the accommodative demand of the HMD pushes vergence outwards, possibly creating double images, 2) the vergence demand of the HMD symbol pulls accommodation inwards, possibly creating blurred images, or 3) some compromise of vergence and accommodation. The absence of reports of blur (except for Subject GG, who reported a degraded symbol image in *all* conditions) suggests that accommodation was not pulled inwards enough to create blur.

One published guideline has recommended that focus be within 0.75 diopter of a one-meter viewing distance (Farrell & Booth, 1975, Figure 3.7-13). The general occurrence of double images with discrepant HMD symbol and screen image distances, and the general absence of double images with congruent distances suggests that the  $\sim 1/2$  diopter HMD focus did not exert a strong influence on vergence, and did not unduly bias the results.

Another potential problem with this study was the calibration of the HMD symbol vergence using an IPD of 62 mm. This setting was valid with Subjects KM, MB, too large for MW and TE, and too small for MC and GG. The effect for MC and GG is to make the symbology appear more distant than intended. The variation in IPD likely accounted for the variation in subject responses for comfort, apparent distance, and differing occurrences of diplopia. Thus, in the current study, no single binocular symbology convergence setting prevented reports of double vision, apparent distance effects and/or viewing discomfort. However, we believe that if the HMD vergence was adjusted for IPD, the results would be much more consistent across observers. The tested configuration, however, represents the way almost all HMDs are used, where there is no vergence modification from user to user.

For each of the three viewing distances, reports of double vision, coupled with viewing discomfort, occur when the HMD symbology and the scenic monitor viewing distances have a (crossed or uncrossed)

disparity of 52 minutes or greater. This 52 minute disparity represents the difference between 36" symbology distance and 45" viewing distance (crossed disparity), or 45" symbology distance and 36" viewing distance (uncrossed disparity). Consensus for double vision and viewing discomfort was found with the 56" symbol distance and 36" viewing distance for an uncrossed binocular disparity of 103 minutes. A more regimented assessment of diplopia thresholds found an average binocular disparity of 38 minutes. This is more than most diplopia threshold studies report (e.g., Duwaer & van den Brink, 1981; Warren et al., 1984), and is likely due to the lack of rigor in the testing (e.g. lax definition of diplopia, small number of trials, only proceeding from small to large disparity, no control over vergence eye movements) and the stimulus conditions (e.g. 2 pixel-wide symbol, lack of detail in the background scene). Nonetheless, the results clearly show that diplopia is a potential issue for the range of distances that occur in a typical faceted flight simulator display system when a binocular HMD is integrated.

If training requirements dictate that a binocular HMD is used in conjunction with a training simulator display system, there are two potential solutions to mitigate potential human factors issues: 1) the use of a large dome-type visual display to minimize variation in viewing distance, or 2) the use of electronic vergence control in the binocular HMD. A dome solution is a straight-forward method of avoiding issues with discomfort, disparity in apparent distance, and diplopia when an HMD is introduced so long as the HMD focus and vergence distances are matched to the radius of the dome. However, this solution increases the cost and footprint of the training system, and also introduces other problems, such as reduced imagery contrast due to internal reflection. The second solution appears to be a viable solution based on the preliminary results of the current study and has the advantage of allowing the integration of binocular HMDs into many existing training systems that currently use the M2DART, VIDS, Simusphere, or WASP. We are currently

working to research and develop this solution for training applications.

## ACKNOWLEDGEMENTS

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