Mitigating Visual Anomalies for Binocular HMDs Integrated with Faceted Simulators

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ABSTRACT

Many existing flight simulators employ faceted displays, with multiple panels of "out the window" visual information presented at different angles and with multiple vertices. Using a head-mounted display (HMD) in a faceted simulator can present visual artifacts not seen in the cockpit, including HMD imagery which appears slanted and with a distorted perspective compared to the imagery presented on the faceted simulator displays. Users viewing information presented across the vertices of the simulator display may notice anomalies due to the HMD imagery being "flat" while the vertex represents a "fold" in the displayed simulator imagery. Binocular HMDs present issues with vergence mismatch when integrated with faceted displays, where the vergence distance (the distance at which the user's eyes converge) to the HMD imagery stays constant while the vergence distance to the simulator imagery varies with head position. These effects could potentially lead to double-imaging (diplopia) and discomfort, and could also diminish the feeling of immersion.

In our previous research, adaptive vergence clearly led to improved comfort and utility compared to fixed vergence, and also led to increased performance on a targeting task. However, some users complained about the distorted perspective, and this may have also affected targeting performance. We have expanded upon those earlier results and examined the effects of mitigating these artifacts using a combination of image perspective warping, rotation and bending. We evaluated both adaptive vergence mitigation only, as well as adaptive vergence mitigation with image warping, rotation, and bending. For each experimental condition, we asked the users to report diplopia/comfort and we also measured their timed performance in a simulated targeting task. We conducted this experiment in a simplified two-facet display system with viewing distance ranging from 36 – 45 inches. Our results show that attempting to mitigate slant and vertex effects have no measureable increase in operator comfort and actually decrease operator performance. In addition, many subjects did not like the fact that the symbology bent into the vertex and moved in space to become coplanar with the out the window displays. Given our previous positive results from adaptive vergence alone, we would recommend not implementing slant and vertex mitigation, but instead just using adaptive vergence mitigation.

ABOUT THE AUTHORS

Dr. Michael Browne is the Vice President of Product Development at SA Photonics in San Carlos, 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

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Dr. 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.

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INTRODUCTION

The results presented here represent the culmination of four years of research in mitigating visual anomalies presented while using an HMD in a faceted simulator. Our initial work (Browne, Moffitt, & Winterbottom 2008) investigated the presence of visual anomalies while using a binocular head mounted display (HMD) in a faceted flight simulator (a simulator with multiple flat "tiles" for presenting "out the window" scenery instead of a dome). These anomalies included subject reports of floating, buried or confusing symbology, doubling of symbology or the background imagery, symbology slanted relative to the simulator screen, and general viewing discomfort. Our primary conclusion was that these visual anomalies could be problematic when integrating binocular HMDs into faceted flight simulators, or even for dome-type display systems when pilots move their head away from the design-eye location.

We extended this work (Browne, Moffitt, & Winterbottom 2009) to evaluate potential solutions to these issues and to attempt to quantify improvements in comfort and performance provided by these solutions. The results of this work suggested that an adaptive vergence configuration, one which automatically adjusted the vergence of the HMD to match the user to screen distance, provided both increased comfort and performance as compared to the nominal fixed vergence condition.

Although we believe our previous work demonstrated that vergence mismatch effects can be mitigated using an adaptive vergence setting, there are a number of other visual anomalies that arise from using an HMD in a faceted simulator. The purpose of our current work was to examine methods of mitigating these anomalies and to determine whether or not these anomalies had any impact on comfort or operator performance.

The two anomalies most commented on by test subjects in our previous experiment were the facts that when they were not looking perpendicular to the screen, HMD symbology appeared slanted with respect to the out the window view, and that in the vertex regions the HMD symbology "bridged" the vertex on a single plane while the imagery displayed on the out the window view was "bent" into the vertex. We assumed that these anomalies would have less impact on operator comfort and performance than vergence mismatch (because for vergence mismatch users would often complain of double imagery) but wondered if the impact in either comfort or performance would be measureable. We also wondered if we could construct a system to ameliorate the screen slant and vertex anomalies.

The specific flight simulator display design of interest for this investigation is the M2DART (Mobile Modular Display for Advanced Research and Training), a simulator display system that can be reconfigured and deployed for a variety of training tasks around the globe yet still provide panoramic imagery (Wight, Best & Peppler, 1998). The key to this design is the use of a faceted display and rear projection. These facets range in viewing distance from as close as 36 inches to a practical maximum of 54 inches. As a pilot looks at different locations in the M2DART, there is the possibility of having significant screen slant or vertex anomalies. The configuration of most other faceted flight simulators is such that the M2DART represents the "worst case" in terms of the potential for screen slant and vertex issues. If these anomalies were not problematic (or could be mitigated) for the M2DART, they would most likely not be problematic for other simulators.

Figure 1 demonstrates a simplified overhead view of a faceted simulator like the M2DART. The green line represents the HMD symbology, presented at a fixed vergence distance. Shown also are two out-the-window (OTW) display facets (one straight ahead, one angled on the right). As the user looks at different locations within the faceted simulator, the relationship between the plane of the HMD symbology (green line) and the display facet changes. When the user is looking straight ahead (Figure 1-left), both are coplanar. When the user looks at the seam between the display facets (Figure 1-center) there is a significant difference between the two images, with the HMD symbology being presented on a flat plane perpendicular to the viewer's line of sight while the OTW displays have an abrupt change in angle at the vertex, preventing the two images from appearing to be coplanar. When the user looks at the right facet (Figure 1-right) there is an angle between the plane of the HMD symbology and the plane of the OTW image. This can be seen by the user as a slant between the HMD symbology and the OTW imagery, which again prevents the two from being seen as coplanar and overlaid.

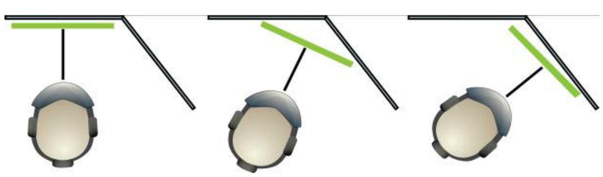

Figure 1. Simplified Overhead View Showing the Geometry Difference Between the HMD Image Plane and Two Adjoining Screens of a Faceted Display System.

Since the development of the M2DART, a variety of manufacturers have developed similar faceted display designs (e.g. Boeing VIDS, and more recently CRVS; L3 SimuSphere and SimusphereHD; Glass Mountain Optics/Flight Safety WASP). These display systems are used widely across the services for a variety of training applications. As such, we expect that as long as there are faceted simulators, the potential exists for these visual anomalies when using a binocular HMD.

Despite the optical equivalence of the HMD symbology and real-world imagery, there is substantial evidence that the pilot switches attention between the two (e.g., McCann, Foyle, & Johnston, 1993; McCann, Lynch, Foyle, & Johnston, 1993). This attention switching is not driven by binocular disparity and focus, but by dissimilar visual imagery and information. This is supported by evidence that observers cannot attend simultaneously to two different sets of imagery/information, even when they are superimposed, and at the same depth (Neisser & Becklen, 1975). Therefore, we postulated that the presence of visual anomalies (such as screen slant and vertex folds) could potentially lead to an increase in attention switching (and an increase in time to perform a task) and designed the performance experiment to test this hypothesis.

Future military aircraft are likely to have an HMD that supports visual cueing with symbology and imagery. The Joint Strike Fighter (JSF) will be the first US fighter jet with a binocular HMD that serves as a primary flight instrument. Although a dome display may be a good solution for the F-35 and other platforms, a number of concerns have been raised about using dome simulators. The first is that if all faceted simulators have to be replaced with dome simulators in order to upgrade existing training simulators for the integration of binocular HMDs, it will be at a large cost. The second concern is the size of the training system footprint and visual system complexity, which drive cost factors associated with training device installation and sustainment. These issues make the integration of a binocular HMD into smaller, more cost-effective faceted displays of particular interest. Although more recent dome display designs have addressed the footprint issue, the cost of upgrading existing systems, and examining the competitive viability of lesser expensive faceted designs remain motivating factors for pursuing this line of research and development.

The above concerns make the compatibility of faceted simulators with binocular HMDs an urgent problem in training F-35 pilots, and for training of pilots of other aircraft if binocular HMDs are adapted for other platforms. The goal of the present experiment was to understand if the visual anomalies such as screen slant and vertex mapping were disruptive enough to impact operator comfort and performance in a significant manner. In our previous work (Browne, Moffitt and Winterbottom, 2009) we demonstrated that vergence mismatch anomalies were significant enough to stimulate a measureable decrease in user comfort and performance. We also wanted to identify the best solutions for improving symbology appearance, viewing comfort and pilot performance for a binocular HMD integrated with a faceted display.

In the virtual world of HMD symbology, electronically shifting the left- and right-eye symbology creates the perception of a change in depth. An inward shift brings the symbology forward, while an outward shift pushes the symbology away. The perceived slant of the symbology can be adjusted by both applying a trapezoidal stretch to it as well as by "rotating" it in stereo space by slightly adjusting the relationship of the symbology in one eye with respect to the other. It is even possible to "bend" symbology both by changing its scaling as well as by changing the orientation of the binocular depth plane on which the symbology is written, such as shown in Figure 2. We used this concept (New Adaptive condition) to attempt to remove the screen slant and vertex issues identified by users in our previous experiments. The primary goal of our current experiment was to examine whether screen slant and vertex issues had effects on comfort and performance and if attempting to mitigate them reduced this impact.

Figure 2. Symbology Bend and Slant Provided by Manipulating Imagery Electronically on the HMD

One of the problems with mitigating slant and vertex effects is that information displayed on the HMD needs to be resampled and "warped". Instead of an exact rectangular matrix of pixels, which are native to the display, this matrix is warped and resampled into a new matrix, much like operating an LCD desktop display at a non-native resolution. This doesn't affect imagery noticeably, but can introduce blur and artifacts into symbology because of its linear structure and narrow line widths. Although this blurring has the potential to negatively impact user comfort and performance, it is a real effect that would be present to some extent in any system that warped and resampled the symbology in an HMD.

METHODS

Observers

Ten observers were selected for this experiment. One observer was excluded due to visual problems associated with recent eye surgery. The remaining nine observers were male and between 33 and 58 years of age. All had experience with the design, marketing or operational use of HMDs. All subjects had worn HMDs and five of the participants were very familiar with HMDs. Four of the subjects were pilots and two were fighter pilots. The authors all participated as observers.

Interpupillary distance (IPD) of each observer was measured with an L8 pupilometer, model NH-L8. Eye dominance was determined by noting which eye was used for sighting through an aperture. Seven observers were right-eye dominant and two were left-eye dominant. Six of the observers wore eyeglasses, three of whom had progressive lenses. All observers had been screened for visual acuity as part of previous experiments.

Stimuli and Apparatus

A Rockwell-Collins Optronics SimEye SXL50 STM binocular see-through HMD was used for our experiment. This HMD, shown in Figure 3, was designed as a simulator HMD for the F-35 Joint Strike Fighter. It has a 1280 x 1024 pixel format, 40 x 30 degree field-of-view (FOV), and monochrome green imagery. Focus of this unit was -0.9 Diopter and the vergence could be set electronically to any distance. This HMD has a see-through transmission of >70% and was set to a nominal luminance of 6.5 foot-Lamberts (fL). This HMD clasps onto an HGU-55/P military flight helmet. Three helmet sizes were available for this study: M, L & XL.

Figure 3. SimEye SXL50 HMD

The design of this HMD for maximum transmittance also meant that it had a severe ghost imaging problem where a second, ghost image of symbology would be visible. This ghost image was in focus, translated and dimmer than the primary image. All subjects were instructed to ignore the ghost image for the purposes of the experiment.

The display directly in front of the subject was a Sharp 60" 120 Hz LCD Display. The flanking display on the left side of the subject was a Sony SXRD 3-panel LCOS (liquid crystal on silicon) rear projection display. Both of these displays had a 1920 x 1080 pixel matrix with a nominal luminance of 35 fL (in the brightest region of the image). These two displays were used to present the out-the-window (OTW) imagery. The monitors had a horizontal dimension of 52", as shown in Figure 4. The straight ahead viewing distance was 36" and the subject position was centered horizontally. This replicates almost exactly the slant angles seen by the user for the front panel of the M2DART system (Wight, Best & Peppler, 1998).

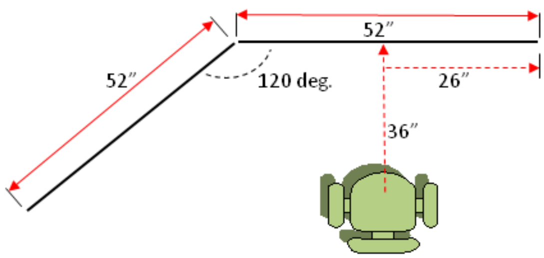

Figure 4. Layout of Simulator Screen and Subject Positioning

A PC computer with nVidia GeForce graphics cards provided the imagery for both the HMD and monitor. A NaturalPoint OptiTracker system, including tracking software, five cameras positioned above the left and front monitors, and a rigid body with optical markers was used. The rigid body (the "target" for the optical trackers) was affixed to the top of the HMD. This tracker transmitted head position and angle relative to the OTW display. Testing took place in an area surrounded by black curtains with a nominal illuminance of 1.5 foot-candles (fc). HMD luminance, monitor luminance and room illuminance were periodically tested to ensure nominal levels were maintained.

The experimental tasks used an HMD reticle and an OTW image of a desert scene including sky, mountains, and a distant city. The HMD reticle, shown in Figure 5, subtended a total of 8 x 6 degrees, with the center circle subtending 1.5 degrees. Each target on the OTW display was a 51 x 22 pixel helicopter image subtending 2.1 x 0.9 degrees at the straight-ahead 36" screen position. The helicopter was gray with a green center dot to aid in centering the reticle on it, and is shown in Figure 6. A photo of a person wearing the HMD and viewing the monitors is shown in Figure 7. Seen above the monitors, on silver posts, are the OptiTracker cameras.

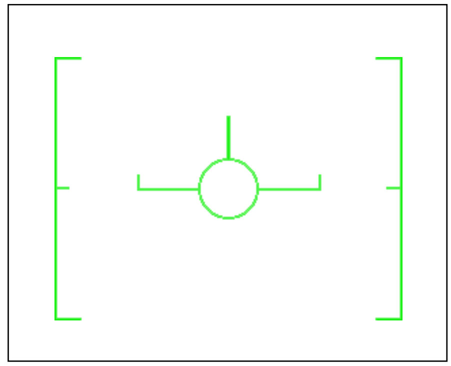

Figure 5. Targeting HMD Reticle

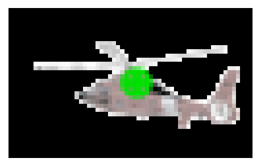

Figure 6. Helicopter Target

Figure 7. Subject Looking for a Target

Procedure

We first fitted subjects with the correct size helmet and then attached the HMD. We then adjusted the HMD in fore/aft, vertical and IPD so that imagery on the HMD was of equal brightness and clarity for all positions within the field of view. Once the HMD was adjusted correctly, we asked subjects to complete four activities as part of our experiment: boresighting, reticle distance preference, viewing comfort, and visual search and performance. Each of these activities is discussed further in the next sections.

Boresighting

To do the initial calibration of the head-tracker, we asked subjects to align the reticle displayed on the HMD with one displayed on the OTW display. If there were any minor errors, we were able to correct them and we then had the subjects do a final boresight check.

Reticle Distance Preference and Calibration

The apparent viewing distance of the HMD reticle can be changed by electronically shifting the images on the left and right eye microdisplays inside the HMD. To account for differences in subjects IPDs and user preference we had subjects electronically position the reticle at a preferred distance from the screen. We used this information to set vergence dynamically for the adaptive viewing condition in the viewing comfort and performance experiments.

Participants began with the straight-ahead 36" target and adjusted the apparent viewing distance of the HMD reticle inward and outward using the left and right buttons of a mouse. They were instructed to put the reticle at the position that they felt would work best for them to complete a targeting task, not necessarily at the same distance as the screen. We then asked them to repeat this for a target at a 42" vergence distance. Figure 8 shows approximately how the HMD imagery appeared relative to the OTW image for near, approximately equal, and more distant vergence settings.

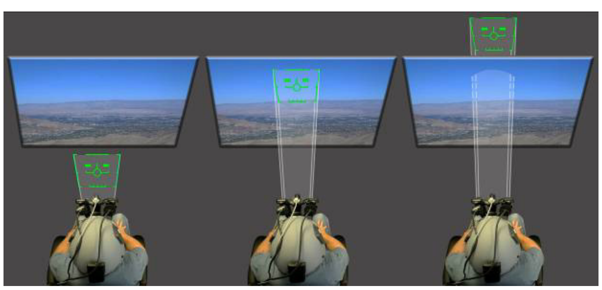

Figure 8. Appearance of HMD Symbology Relative to OTW Imagery as the Viewer Electronically Adjusted Vergence Settings on the HMD

Viewing Comfort Rating

Subjects provided a rating of viewing comfort for seven target positions—distributed on the forward screen and ranging in distance from 36 to almost 46 inches. The locations of the targets on the screen and their corresponding vergence distances are shown in Figure 9 (the targets are enlarged for better viewability in this paper).

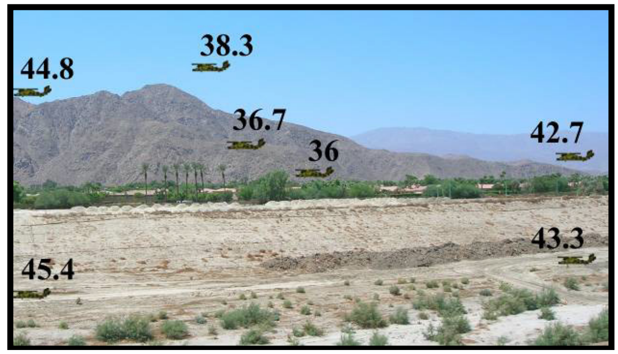

Figure 9. Location of Targets on OTW Display Along with Vergence Distances

The targets were sequentially presented in random order. Observers positioned the HMD reticle over the target and provided a rating of viewing comfort while looking at both the target and background (presented on the OTW display), and the HMD reticle. The ratings were: (1) not uncomfortable to view, (2) somewhat uncomfortable to view, or (3) very uncomfortable to view.

The Likert items of not/somewhat/very uncomfortable were adapted from similar scales with approximately equal intervals (e.g., Babbitt & Nystrom, 1989). Subjects were instructed that "Not uncomfortable to view" means that the image may look unusual, but not blurry, double or confusing. You could easily view this image for a period of time. "Very uncomfortable to view" means the image may be blurry, double or confusing—something you would not want to view for any length of time. "Somewhat uncomfortable to view" describes an image intermediate between these two extremes.

Three viewing conditions were tested: (1) a fixed reticle distance of 42 inches that is an intermediate value between the two distance extremes (Fixed), (2) an adaptive vergence that adjusts the reticle to the target distance—keeping the reticle at a right-angle to the observer line-of-sight (Old Adaptive), and (3) a "new" adaptive distance that adjusts the reticle to the target distance *and* slants the reticle to be conformal to the simulator screen and bent into the vertex (New Adaptive).

Visual Search and Performance

In this investigation we asked whether the HMD symbology configuration in a faceted simulator is simply a comfort and perception issue, or if subject performance in a timed number matching trial is also affected. Subjects were asked to search for targets located at one of seven locations on the screen. These locations ranged in distance from approximately 36” to 45.4".

When a target was located, the subject aligned the HMD reticle with the target and the reticle changed to a “missile lock” configuration (four arrows surrounding the targeting reticle, as shown in Figure 10). After one second of accurate alignment (representing a “missile lock”), a three-digit number was displayed on the reticle and another three-digit number was displayed on-screen. The size of the numbers was chosen to be just big enough to be read by a subject with normal visual acuity (when read alone, outside of the timed targeting task subjects could identify the numbers accurately). The two numbers (spatially adjacent, but presented by two different means) were compared by the participant. The participant was instructed to push the left mouse button if they were the same, and the right button if different. If an error was made, the subject was required to enter the correct response. After a correct response, a new target randomly appeared at one of the remaining locations, and the subject continued the search task.

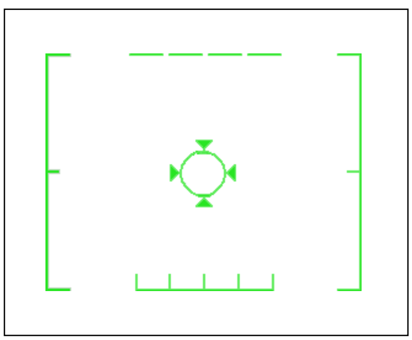

Figure 10. Lock Reticle

The three reticle conditions tested in the Viewing Comfort experiment were also tested in this experiment. Three sequential trials were run for each condition, and the presentation order of the reticle conditions was different for each participant.

We designed this experiment to replicate conditions in a real simulator environment where operators must redirect their attention between HMD symbology and on-screen imagery. Our hypothesis was that response times should be longer where there was a significant difference in distance between the target presented on the HMD and the one presented on the faceted simulator. We believed this to be so because subjects would have to switch their attention between the two sets of numbers (representing a realistic situation where pilots are concentrating on HMD-supplied targeting symbology while also concentrating on the target itself in the “out the window” faceted display). The primary data from this task were total time to find and compare numbers at the seven target locations. We also recorded single target times from acquisition to response.

RESULTS

Viewing Comfort Ratings

Rating data were analyzed with a two-way repeated measures analysis of variance. The effect of vergence (old adaptive, new adaptive and fixed) was significant $F(2,16) = 9.41$, $p < 0.01$. This effect can be seen in Figure 11 as the Fixed Vergence condition resulting in overall higher average ratings of viewing discomfort. The effect of Target Position was not significant. The interaction of Vergence with Target Position was highly significant, $F(12,96) = 8.67$, $p < 0.001$. This significant interaction took the form of the Fixed condition causing more viewing discomfort than either the Old or New Adaptive conditions at the three closest target positions, while converging on similar comfort ratings at the four most distant positions.

Figure 12 shows a Marimekko chart presentation of the comfort data. We feel this type of chart provides a good graphical representation of user comfort as a function both of viewing condition and of viewing distance. Each cell depicts the count of each rating choice for the 9 participants. The proportion of each cell which is shaded white gives an indication of the comfort of each viewing condition. For example, all subjects rated the New Adaptive viewing condition at 36” (located in the lowest, left-most cell) as comfortable, thus it is shaded completely white. On the other hand, the Fixed viewing condition at 36” and 36.7” target distances was rated very uncomfortable by almost every subject, so that its cell (upper left-most cell) is shaded almost completely black.

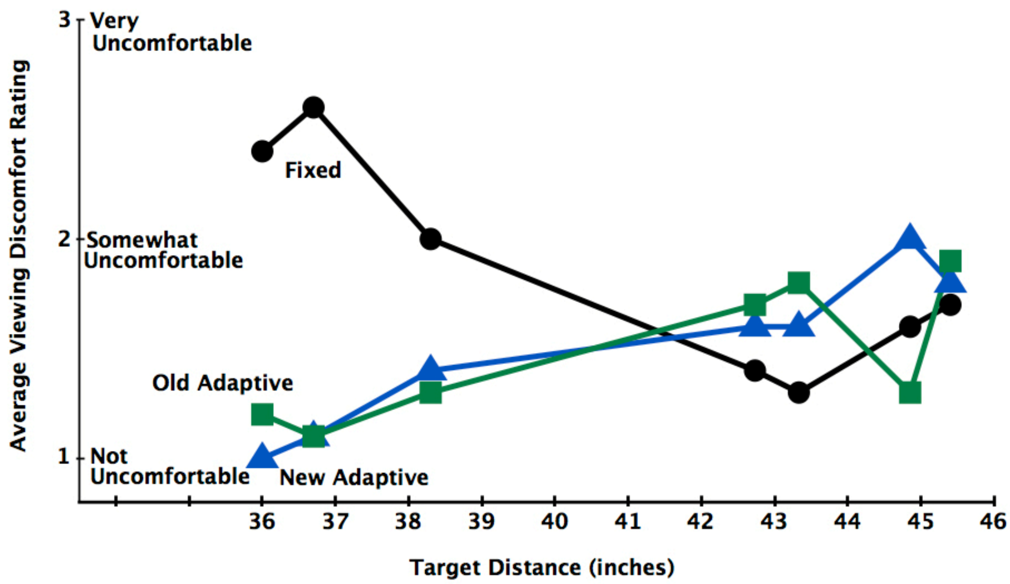

Figure 11. Viewing Discomfort as a Function of Target Position and Vergence Condition

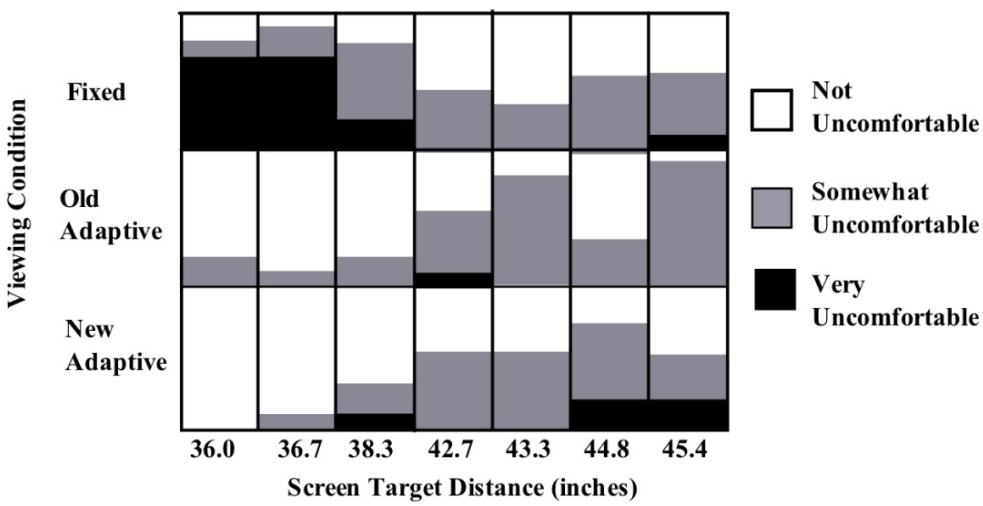

Figure 12. Marimekko Presentation of Comfort Data

The fixed reticle distance of 42 inches provided a vergence location that was behind the screen target at the three closest positions. We have previously observed that this is a discomfiting view, and is often described as *incorrect* and *confusing*. In contrast, both adaptive conditions showed less viewing discomfort at these same screen distances. We attribute this to the HMD reticle being positioned at or nearer than the screen, and never behind the screen.

At the four most distant target distances, the fixed 42-inch reticle appeared closer than the screen target. Observers were well aware of this depth, but never described it as incorrect or confusing. Regardless of whether the reticle was at a fixed distance, adapted to the observer at a right angle, or adapted *and* slanted—ratings converged on *somewhat uncomfortable* for the four most distant targets positioned toward the edges and corners of the forward screen.

In addition to the comfort ratings, we also asked the subjects to provide verbal feedback on the imagery at any time in the experiment. The following is a summary of these verbal comments:

- it was annoying that the reticle moved around (jumped back and forth in depth) in the new adaptive condition (multiple complaints)
- having the reticle slanted with respect to the screen was not bothersome
- symbology appears to "scintillate" for the new adaptive case at the vertex

- some adaptive targets were a little blurry
- did not like the symbology folding into the vertex (multiple complaints)
- did not like the fixed vergence condition when viewed at a slant (both adaptive conditions were okay)
- thought the new adaptive reticle needed to rotate quicker
- did not like seeing symbology shift around, this is unnatural and does not occur in the real aircraft (for New Adaptive condition)
- felt like bending the symbology into the vertex only called attention to the fact that the display was faceted (multiple complaints)

Visual Search and Performance

In previous experiments we calculated the median search time (time to find the target and achieve "lock"), the median response time (time between "lock" and a correct response on the number matching task) and the total time (sum of search and response times). We found that the search time and total time were dominated by the disproportionate amount of time subjects spent searching for the next target. Because of this, in this experiment we only examined median response time. We defined response time as the elapsed time between target acquisition and a correct manual response. While differences in background imagery and target location could affect the time to find each target, the effect on response time should be minimal.

The median of the three repetitions was used for analysis and is shown in Figure 13, along with error bars corresponding to the median response time standard error. There was one outlier—with one subject requiring over 30 seconds to respond to a target at the edge of the screen, compared to most times being between 0.9 and 1.4 seconds. Given that this was a single outlier among 189 data points, we replaced that one data point with the average of the other eight subjects for that condition.

Performance data were analyzed with a two-way repeated-measures analysis of variance. The effect of vergence (old adaptive, new adaptive and fixed) was significant $F(2,16) = 9.01$, $p < 0.01$. This effect can be seen in Figure 13 as the Old Adaptive vergence condition having consistently short response times. The effect of Target Position was also significant, $F(6,48) = 2.45$, $p < 0.05$. The interaction of Vergence with Target Position was highly significant, $F(12,96) = 3.17$, $p < 0.001$. This significant interaction took the form of longer response times for the Fixed 42-inch vergence condition at the straight-ahead 36-inch target position, and for the New Adaptive vergence condition at the 45.4inch target distance in the corner of the display.

DISCUSSION

We investigated the effect of mitigating slant and vertex effects for a binocular HMD integrated with a faceted OTW display. The two measures of this effect were self-reported comfort values and a performance time to correctly identify a target.

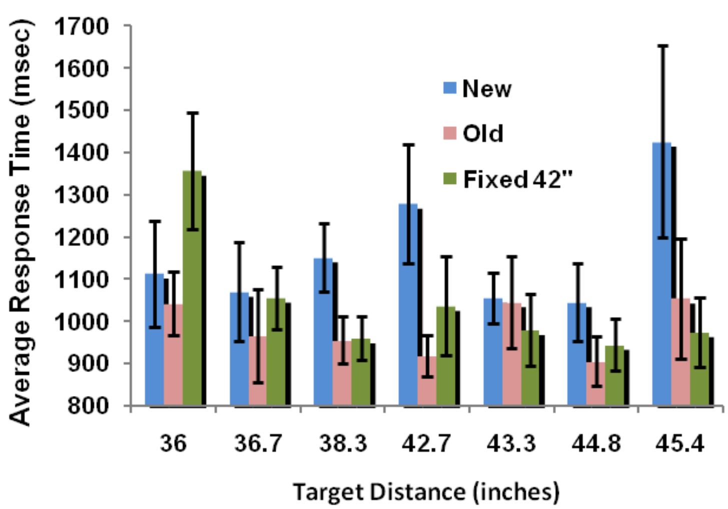

Figure 13. Response Time as a Function of Target Position and Vergence Condition

The comfort data for all conditions gradually increase to "somewhat uncomfortable" as distance increases. There are a number of reasons that this occurs, including the fact that the slant angle between the

HMD and OTW imagery also increases, becoming distracting due to slant for the Fixed and Old Adaptive condition, and distracting due to image warping in the new adaptive condition. This could also be due to the ghost image present on the HMD, which tends to be distracting. In addition, this discomfort may be caused solely by the fact that viewing "the real world" on a slanted plane such as is presented by the OTW display is unnatural even without accounting for HMD symbology.

Our common human experience is to view the world as objects layered in a three dimensional space. Even when we do view two dimensional representations of the real world, as with a television monitor, the field of view is small and the presentation is passive, as if viewed through a portal and not active and immersive in most cases. Viewing a large display at a close distance, such as presented in this experiment, may cause some discomfort.

In our previous experiment (Browne, 2009), which had a similar condition to Old Adaptive, most subjects reported a "not uncomfortable" response at these positions (although there was a higher reported number of "very uncomfortable" ratings as well in our previous work, reinforcing the large variability in subjective responses to viewing comfort questions).

The performance data in Figure 13 at the closest viewing distance confirm our previous results where large vergence mismatches caused not only discomfort but poorer performance. However, a significant increase in response time for fixed vergence was only observed for the closest distance (largest mismatch).

We did not expect to see increased response times for the New Adaptive viewing condition compared to the Old Adaptive condition, and the comfort ratings did not indicate that the New Adaptive condition was statistically any less comfortable than the Old Adaptive condition. There was significant variability in the response times for the New Adaptive condition, which mirrored the large variability in comments on that condition given by subjects. Some subjects found no problems with this condition while others thought it to be very disconcerting. Variability in the New Adaptive condition is especially present in the viewing distances that also have the longest response times.

The reason subjects performed worse for the New Adaptive condition may be that the numbers on the HMD imagery were harder to read for the New Adaptive case due to the image warping and resampling, as noted by some observers in their comments. Although we could make these numbers somewhat easier to read with better anti-aliasing, any warping or resampling of the HMD symbology, such as is necessary for slant and vertex manipulations, will also reduce the readability of the symbology. This undesired side-effect may provide additional reason to not perform slant and vertex mitigation for an HMD used in a faceted simulator.

Another reason that subjects did worse with the New Adaptive condition was that the bent and rotated symbology was confusing and unnatural compared to what they see in the real aircraft. Helmet symbology that would appear to be parallel to the horizon in the jet appeared unnaturally bent to follow the angle of the facets when viewed along seams between facets. When viewing the OTW scene by itself on a faceted display system from the design eye point, pilots do not notice the converging angles produced by adjacent facets when viewing across a vertex. When viewing the same OTW scene, with the HMD symbology bending to match the OTW scene as the pilot rotates his field of view across the display, the converging angles of the display were highlighted. During the experiment this effect was very pronounced when the subject rotated his head side-to-side across a seam between two opposing facets, causing the HMD reticle symbology to be bent going into the apex and un-bent going out of the apex to match the angle of the adjacent facets. This is distracting because the "real" HMD symbology in the fighter jet would never appear to bend. The result of the perceived "bending" of the display symbology was to highlight the previously un-noticed opposing angles of the OTW scene across the adjacent facets, destroying the subject's sense of immersion. This effect is likely to be even more pronounced using actual HMD symbology with longer horizontal and vertical line images than the relatively compact HMD reticle used in the experiment.

Over the past four years we have researched visual anomalies presented while using a binocular see-through HMD in a faceted simulator. This work is of value due to the proliferation of binocular HMDs for use in fighter jets and the desire to not have to replace existing faceted simulators with dome simulators, although even dome simulators will have some of these issues when pilots move out of the design eye location.

Data from our first experiment (Browne, 2008), showed that almost 80 percent of subjects saw double imaging for the largest difference in vergence (vergence differences that were realistic for current flight simulators). Our second experiment (Browne, 2009) evaluated five different methods of mitigating vergence mismatch effects. Two of the methods were fixed vergence settings at different vergence positions (one converged at the point directly in front of the subject, and one, similar to the current Fixed, at the intermediate position). One method was adaptive vergence (Old Adaptive), one method used monocular symbology (no vergence problems, but poorer performance than binocular) and one used on-screen symbology (no vergence problems, but not realistic). Adaptive vergence provided the best performance and was second in comfort with on-screen being the most comfortable.

For all of these experiments, a common observation by subjects was that the symbology slanted with respect to the screen at larger viewing angles and that the symbology bridged the vertex.

In the current experiment we implemented a way of reducing the screen slant and vertex bridging and investigated whether or not it had a positive effect on comfort and performance. Although this method did reduce the screen slant and vertex bridging, the disadvantages in user performance and acceptance of the symbology degradation due to resampling and warping outweighed the advantages of having the HMD symbology appear conformal with the screen.

Based on all of our research activities into integrating a see-through binocular HMD into a faceted simulator, we would recommend that adaptive vergence be implemented without the resampling and warping necessary for conformal symbology.

To validate using this approach in a real training environment, additional experimentation would have to be done in a real flight simulator for a realistic duration (around 90 minutes per trial) using dynamic imagery and symbology which is realistic for a fighter jet.

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