



HELMET-MOUNTED DISPLAYS FOR USE IN AIR FORCE TRAINING AND SIMULATION

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This technical report has been reviewed and is approved for publication.

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ABSTRACT

This report provides a review and analysis of the published literature on head-mounted displays (HMDs). In doing so, this report also draws heavily from the basic vision research literature in order to help provide insight for future design solutions for HMDs. In particular, we discuss several key perceptual issues that are relevant to the use of HMDs. The issues discussed are: (1) brightness and contrast; (2) accommodation-vergence synergy; (3) field of view; (4) binocular input; and (5) head movements. This review of the literature is intended to anticipate and solve perceptual issues associated with two particular HMD applications: (1) simulation of off-bore sight (OBS) targeting and (2) full field-of-view out-the-window (OTW) simulation for deployable flight training. Additionally, several technology issues important to the continued development of HMDs are discussed. This report concludes with a set of recommendations for the design and use of HMDs for OBS and OTW flight training applications.

REVIEW AND ANALYSIS OF HELMET-MOUNTED DISPLAYS FOR USE IN AIR FORCE TRAINING AND SIMULATION

SUMMARY

This paper provides a review and analysis of some of the visual perceptual issues related to the use of helmet-mounted displays (HMDs) for training and simulation applications at Air Force Research Laboratory, Warfighter Readiness Research Division, Mesa, AZ. A typical HMD system is presented, which is composed of several parts: an image generator, a display device attached to the head or helmet, relay optics, a combiner if the imagery is seen as superimposed on another display screen or superimposed on the outside world, and a head-tracking system.

First, although the focus of this report is perceptual issues in the use of HMDs, a brief summary of current technology relevant to HMDs is presented. This summary includes a review of currently available visual display technology as well as some predictions for future display technology that may be suitable for helmet-mounted use. A brief summary of currently available head tracking technology is also included. Next, an analysis of perceptual issues related to the use of HMDs in two specific situations is given: (1) simulation of off-bore sighting, (OBS) and (2) simulation of out-the-window (OTW) viewing. For simulation of OBS, monocular HMDs may be used while the user views the OTW display of a flight simulator. We consider the use of a monocular HMD to expand the capabilities of the current Mobile Modular Display for Advanced Research and Training (M2DART) at Air Force Research Laboratory (AFRL), Mesa, AZ to include features similar to that of the Joint Helmet Mounted Cueing System (JHMCS) currently being fielded in various airframes (F-15, F-16, and F-18). In this HMD application, where only monochrome symbology is displayed, the technology demands are fewer compared to the OTW HMD. A monochrome image source with a relatively narrow field of view would be suitable.

Binocular, wide field of view HMDs provide one approach for simulating OTW imagery, particularly in deployable training applications. A high-resolution display having a field of view greater than 100 degrees is required. Furthermore, motion artifacts in the display need to be minimized as much as possible. Additional requirements include: interocular differences in luminance no greater than 25%, a rotational difference no greater than 3.4 arcmin, horizontal or vertical differences in image size no greater than 1.5%, vertical misalignment less than 5 arcminutes, and horizontal misalignment less than 8.6 arcminutes. The update lag between head movements and update of display imagery needs to be less than 16.7 msec. A table summarizing these findings is located on pages 38 and 39.

Based on the review of previous HMD research issues and a survey of current technology, recommendations for future research projects are also given:

(1) Depth of Focus. In simulating OBS using a monocular HMD worn in a flight simulator, the plane of focus of the symbology on the HMD should match the viewing distance to the display screen of the simulator so that all images are in focus. This will not be an issue for dome-type display systems assuming the focal length of the HMD imagery has been adjusted to match the radius of the dome. However, for faceted display systems such as the AFRL M2DART, Boeing VIDS III, Link Simulation and Training Simusphere, and Glass Mountain Optics WASP displays, the distance from the viewer to the display surface varies with direction of gaze. The rear-projected imagery and HMD imagery will therefore be at differing depths and the observer may not be able to maintain focus on each image simultaneously. The results of a study conducted at AFRL, Mesa to evaluate whether differing focal distances will hinder the feasibility of simulating OBS using a monocular HMD in the M2DART are summarized on page 16.

(2) Accommodation-Vergence Mismatch. When simulating off-bore sighting with a monocular HMD worn in a flight simulator, or simulating OTW viewing with a binocular HMD, the stimulus to accommodation will be the imagery of the HMD and/or display screen of the simulator. However, when the user changes his or her vergence angle to binocularly view a virtual target in the synthetic scene, the vergence angle can be mismatched relative to accommodative demand. There are three potential effects of accommodation-vergence mismatch: (1) eye strain or visual discomfort; (2) blurring of imagery (depending upon display brightness and contrast); and (3) misperceived size, depth, speed, and/or distance via the operation of perceptual constancy.

(3) Binocular Rivalry. In simulating off-bore sighting, one eye views the reticle and both eyes view the OTW imagery. In this case, the existence of interocular differences in stimulus characteristics has the potential to produce binocular rivalry. In viewing OTW imagery with a binocular HMD, both eyes will view the out-the-window scene of an ongoing mission. Off-bore sighting can be also be simulated using a binocular HMD by presenting the appropriate symbology to one eye (or both) in addition to the OTW imagery. In this case, the existence of small, unintended interocular differences in stimulus characteristics may occur due to imprecision of mounting and alignment, which may also produce rivalry. Luning, which is often present in binocular displays with partial overlap, is also thought to be caused by rivalry. It is therefore important to determine which stimulus parameters produce or minimize rivalry and whether training or practice can help mitigate such effects.

(4) Field of View. This is primarily an issue for simulation of OTW viewing with a binocular HMD. Field of view can have a significant effect on performance of tasks relevant to pilot training. It is important to determine what size field of view is required and how field of view requirements need to be weighed against other requirements, such as resolution and binocular overlap. If high resolution is a

driving requirement, for example, field of view must necessarily be smaller. If depth cues are important in a particular HMD application then full binocular overlap with binocular disparity across the field of view may be a requirement. This would also necessitate a smaller field of view. Technology development is needed to address this issue.

(5) Binocular Overlap and Convergent versus Divergent Displays. In simulating OTW viewing, it is important to determine the perceptual implications of using either convergent or divergent binocular displays. In particular, one should determine how the convergent versus divergent systems relate to half-occlusions, visual suppression, luning, and field of view, and whether one type of display is better than the other or whether a full-overlap display should be considered.

(6) Head tracking of voluntary head movements. In simulating out-the-window viewing, the display imagery must be shifted in a direction opposite to voluntary head movements to mimic an environment-centered frame of reference. One potential problem is that the time required to measure the head movements with the head tracking system and update the display creates a temporal lag that impairs perception and places constraints on the gain of the head tracking system. It is therefore important to investigate the relationships among head-tracking accuracy, lag, and size of head movement to determine an acceptable set of parameters.

(7) Head tracking of involuntary head movements during training or rehearsal. If, during mission training or rehearsal, the user employs an HMD in an environment that causes acceleration or vibration, the head will execute involuntary head movements, which, in turn, elicit a compensatory and opposite vestibulo-ocular reflex (VOR) eye movement. The VOR eye movement impairs viewing of the HMD because the image moves with the head, which renders the VOR response as inappropriate. One approach for correcting inappropriate VOR responses is to measure the involuntary head movements with a head tracker and shift the image on the HMD by the same magnitude and a direction opposite to the head movement (in the same direction as the eye movement). One problem with this technique is that the head tracker would likely not be accurate enough to fully compensate for the small amplitude VOR response. It is therefore important to determine to what degree HMDs will be used for mission training and rehearsal in environments involving acceleration or vibration. This could occur if mission training or rehearsal were conducted on an aircraft carrier or transport plane while enroute to a new mission. Significant vibration or acceleration would also occur if the HMD were used in conjunction with a moving base simulator or motion seat.

INTRODUCTION

Recent demands for deployable training systems and the adoption of HMDs in fielded aircraft for off-bore sighting (OBS) have renewed interest in HMDs for flight training applications. An HMD presents symbolic or pictorial information to a pilot or other user while allowing changes in head position. Current generation HMDs use miniature displays mounted on a helmet and relay optics that present imagery to the user's eyes (Beal & Sweetman, 1997; Velger, 1998). These displays offer some advantages over traditional displays, such as increased situational awareness in augmented visibility situations (Velger, 1998). HMDs would also be useful in mission training and rehearsal simulations due to their portability.

If implemented properly, HMDs can offer advantages over traditional displays, such as increased situational awareness and ease of mobility. Thus, HMDs are increasingly being considered for use in a wide variety of applications, including surgery and other medical applications, remote vehicle operation, flight simulation, and automobile racing (Melzer & Moffitt, 1997; Velger, 1998).

Despite the potential advantages of HMDs, their development through the years has not been uniform (Ruston, Mon-Williams, & Wann, 1994; Sheedy, & Bergstrom, 2002). Although Peli (1998) notes that visual effects during the use of an HMD were similar to those of a desktop display, Keller and Colucci (1998) state that HMDs have often disappointed real world users. While HMDs have been used successfully in certain applications, their use in other applications has been troublesome (Velger, 1998). This is due, in part, to the fact that HMDs can create significant perceptual problems not found with traditional displays (Melzer & Moffitt, 1997). For example, Wenzel, Castillo and Baker (2002) found that aircraft maintenance workers who used a HMD for training purposes reported problems such as eyestrain, headache, nausea, and dizziness. Morphew, Shively, and Casey (2004) found that self-reports of nausea, disorientation, and oculomotor strain were greater with an HMD compared to a standard computer monitor for a Unmanned Aerial Vehicle control task. Hakkinen (2004) reports similar problems when a monocular HMD was used when performing a text-editing task. Kooi (1996) reported significantly greater eyestrain with the use of HMDs compared to a standard computer monitor. Simulator sickness has also been reported with the use of HMDs and can be caused by a number of factors (Ehrlich, 1997; Draper, Virre, Furness, & Gawron, 2001; Draper, Virre, Furness, & Parker, 1997).

In order to address these issues for improved future applications an understanding of the perceptual issues underlying these phenomena is necessary. To that end, this paper provides a review and analysis of some of the visual perceptual issues related to the use of helmet-mounted displays in two situations: (1) simulation of off-bore sighting, and (2) simulation of OTW viewing. The published literature on HMDs as well as basic perceptual processes is reviewed and perceptual issues identified that

are relevant to HMD systems currently available and likely to be commercially available in the near future. A summary of currently available HMD systems suitable for use in simulation of off-bore targeting and OTW viewing applications is also included. We also provide some discussion of HMD components, such as visual display technology, head tracking systems, and optics. However, we are primarily concerned with perceptual issues that may arise with the use of HMDs in specific applications. For a more thorough description of HMD engineering design and technology issues see, for example, Velger, 1998 or Melzer and Moffit, 1997. Finally, recommendations for future areas of research to investigate certain perceptual issues will be given.

BASICS OF HMDS

A typical HMD system is composed of several parts: an image generator, a display device attached to the head or helmet, relay optics, a combiner if the imagery is seen as superimposed on another display screen or superimposed on the outside world, and a head-tracking system (Velger, 1998).

The HMD can be a monocular system (Figure 1); in which synthetic imagery is presented to only one eye of the user (the other eye sees the real world). This situation involves one image source and one set of optics, therefore the HMD is relatively lightweight. The use of monocular HMDs creates the potential for perceptual problems such as binocular rivalry and visual discomfort. The HMD can also be a biocular system, in which the same imagery is presented to both eyes of the user (Rogers & Freeman, 1992), or a binocular system, in which slightly different imagery (i.e., imagery with binocular parallax) is presented to the two eyes (Klymenko et al., 1994). Binocular displays have the advantage of providing stereoscopic depth information to the user but significant disadvantages of greater complexity, alignment, and precision mounting issues. They will also require the use of two separate visual channels with slightly different perspectives. An example of a binocular, see-through HMD is shown in Figure 2 (left) as well as a binocular occluding HMD (right).



Figure 1. Left, Monocular see-through (courtesy of Microvision) and right, monocular occluding HMD (courtesy of LiteEye).



Figure 2. L3 Communications Advanced HMD (left, courtesy of L3 Communications) and Kaiser SR 80 binocular HMD (right, courtesy of Kaiser Electro-Optics).

An ideal HMD would have high resolution, very short imagery-update lag, and be lightweight with an appropriate center of mass (Velger, 1998; Wood, 1992). For OTW simulation, a very large field of view and large area of binocular overlap would be desirable. In reality, however, trade-offs exist among these characteristics. Improving one characteristic will come at the expense of another characteristic. For example, increasing the field of view will require larger optics and a corresponding increase in weight. Center of mass will therefore also be affected. Overcoming these limitations will require new technology.

The information displayed on an HMD can be as simple as an aiming reticle or alphanumeric symbols or may consist of complex full-color moving imagery (Velger, 1998). Some HMD applications use conformal symbology. Conformal symbology refers to world-stabilized symbology that conforms to the outside world (i.e., symbology linked to an environment-centered frame of reference) such that the symbology changes with head position. Conformal symbology is difficult to implement because the position of the head must be measured and the symbology updated quickly to mimic the shift in scene with changes in head position that occurs in the real world. Temporal lags in the measurement of head position impair human performance and create disorientation and discomfort because lags delay the update of imagery relative to the head movement (Long & Wickens, 1994; Velger, 1998) and produce a mismatch between proprioception (sense of body position) and vision. Such a situation exists when the HMD displays information that substitutes for the real-world view (Ineson, 1991; Kaye et al., 1990; Adam, 1994; Swenson et al., 1994), such as when simulating OTW viewing for training or mission rehearsal purposes.

TECHNOLOGY ISSUES

Visual Displays

Current Technology

There are many types of visual displays that could potentially be used in helmet-mounted applications. Miniature monochrome cathode ray tube (CRT) displays have generally been used with HMDs in the past due to a lack of viable alternatives. CRTs do offer high luminance output, low cost, durability, and desirable temporal characteristics. Significant disadvantages of CRT displays, however, include their relatively high weight, large size, and high power requirements.

Other types of displays are now beginning to replace CRTs for use in HMDs. The most promising visual display as a replacement for CRTs for use in HMDs is the Liquid Crystal on Silicon (LCoS) display. These displays are relatively fast, have good light output, low power consumption, low weight and small size, high fill factor, and relatively high resolution. LCoS chips have a greater potential to achieve high pixel counts and manufacturing costs are lower compared to some other technologies (McLaughlin, 2002). Limitations of LCoS displays include some brightness limitation due to heating of the liquid crystal, color shifts over time, and limitations to contrast due to anisotropy and polarization coupler efficiency. There are also some limitations to switching time due to capacitance (Pinho, 2004). Another potential disadvantage of LCoS displays in HMD applications is the requirement for an illumination source, which must be mounted in front of the LCoS panel. This may impose some limitations on the configuration of the optics for a head mounted design. Furthermore, the lamp may periodically need replacement. However, the development of high output light emitting diodes (LEDs) alleviates these concerns to some extent. Current chip designs also cause the LCoS pixels to be illuminated for an entire video frame (typically 16.7 milliseconds). This hold-time increases the light output of the device, but may cause motion artifacts such as blurring or double images (see e.g., Winterbottom, Geri, & Pierce, 2004 and Lindholm, Pierce, & Scharine, 2001). These artifacts are clearly undesirable in military simulation applications, particularly fast jet simulation. These motion artifacts can be predicted through analyses in the spatiotemporal domain if the properties of both the display and the observer are known (Watson, Ahumada, & Farrell, 1986). An additional complication for helmet-mounted applications, particularly OTW applications, is that the imagery must move when the head moves. Movement of the head will cause significant blurring, or loss of definition, if the full 16 msec hold-time is maintained. A new type of LCoS, a ferro-electric LCoS (FLCoS), which has recently been introduced (see for example <http://www.crlopto.com/>), may provide a solution to the pixel hold-time issue. The new FLCoS is significantly faster than even the standard LCoS. Provided that sufficient illumination is available, it is possible that the pixel hold-time on the FLCoS could be reduced sufficiently

(e.g., < 4 msec) to reduce motion artifacts. Several HMD manufacturers are now using FLCoS (e.g., Kaiser SR80 and SR100, L3 Communications Advanced HMD, and NVIS nVisor).

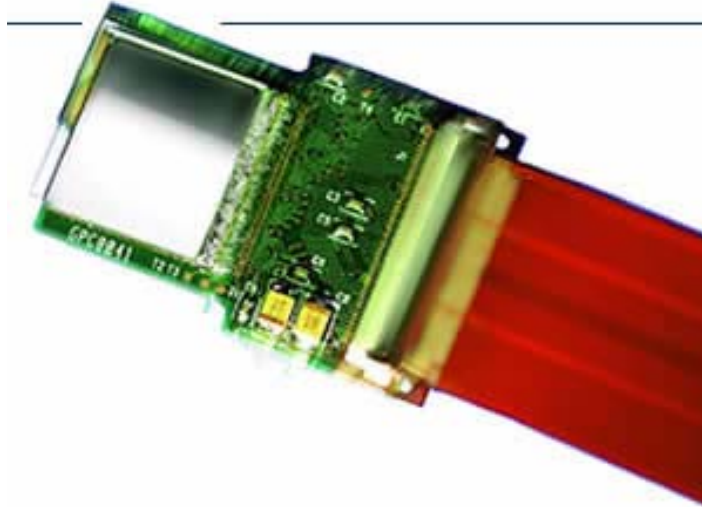


Figure 3. An FLCoS display panel (Used with permission of CRL Opto Ltd.).

Active matrix liquid crystal displays (AMLCDs) also have the advantage of low weight and small size and have good image quality and color. However, they also require a lamp and typically have temporal characteristics that are too slow for applications involving moving imagery, such as fast jet simulation. Head motion will also result in significant blurring with LCD displays. LCDs also have a pixel hold time of one frame, resulting in the additional temporal issues described for the LCoS displays. Additional drawbacks of LCD's include some brightness limitation due to heating of the liquid crystal, color shifts over time, and limitations to contrast due to anisotropy and polarization coupler efficiency. There are also some limitations to switching time due to capacitance (Pinho, 2004). These are similar to the limitations to LCoS displays – both use liquid crystal technology.

Electroluminescent displays (or active matrix EL displays) have high luminous efficiency and brightness (300-500 ft-L) as well as high contrast ratios 1:50-1:100 (Monarchie et al., 1995). These devices use alternating current to excite a thin-film phosphor. The phosphor layer is sandwiched between insulating layers and deposited on a glass substrate with transparent electrodes (Post, 1999). Miniature devices have been manufactured for head-mounted use, but HMDs that utilize this display technology are not widely available.

Virtual retinal displays (VRDs) have been developed by Microvision (<http://www.mvis.com/>) and are commercially available. This type of display presents images to the visual system by scanning the

images directly onto the retina using a diode laser light source and thus eliminating the display screen. The potential advantages of such a system are increased resolution, contrast, brightness, and color quality, and decreased weight (Businessweek Online, 1999). The bright high-resolution image source can be located off-helmet and its image presented to the helmet and pilot via fiber-optic image guides (Naor et al., 1987; Thomas et al., 1989; Velger, 1998, pp. 109). One disadvantage of this display device for helmet-mounted applications is the small exit pupil. Slippage of the helmet or large amplitude eye movements may cause portions of the image to disappear from view. Resolution of current VRDs (800x600) are sufficient for display of symbology in monocular applications, but would need to be increased for binocular OTW applications with complex imagery.

Digital Light Processing (DLP) display devices (or Digital Micro-Mirror Display or DMD) created by Texas Instruments (<http://www.dlp.com/>) could also be used in head-mounted applications. A DMD display operates using tiny addressable micro-mirrors. These mirrors pivot between two orientations to either reflect light out through the lens to the observer, or reflect it into an absorptive material. The micro-mirrors can be switched at high rates of speed (up to several thousand times per second). The rapidly moving mirrors are used to modulate brightness by varying the amount of time the light is displayed during the refresh period (pulse-width modulation). DLPs have the highest brightness capability of all the current digital technologies and require the simplest optics. However, the number of pixels that can be placed on one chip may be limited and they are currently more expensive to manufacture (Pinho, 2004). Furthermore, the same temporal issues apply to DLPs as noted for the LCoS and LCD displays.

As noted above, most, if not all, currently available digital displays exhibit temporal artifacts, which become quite evident for rapidly moving imagery. Both the LCoS displays, and current DLPs, for example, are designed to display one video frame for an entire refresh period (typically 16 msec). In addition, many current DLP projectors are field sequential, so multiple images of different colors may be displayed during the course of one frame. Field sequential displays may exhibit color breakup – particularly where the pulse width modulation of each of the colors is spread throughout the entire 16.7 msec frame. For HMDs, where weight is a significant concern, a fast digital display (whether DLP or FLCoS) is likely to be single panel color sequential. Additional development work is needed to reduce this and other temporal artifacts in these types of digital displays, particularly for HMDs, where head motion may exacerbate the problem. These artifacts can be predicted when the temporal characteristics, and other properties of the display, are known (Lindholm & Scharine, 2000; Post, Nagy, Monnier, & Calhoun, 1998). Post et al (1998), for example, developed an equation that can be used to predict the

display refresh rate necessary to reduce color breakup to below a detectable level for a given target luminance level, contrast, and rate of motion.

Future Technology

A recent development in display technology is the laser projector. The laser projector is a proof-of-concept display device currently under development by Evans and Sutherland Inc. (E&S) and Air Force Research Laboratory (AFRL). The goal of this E&S/AFRL development effort is to develop a true 20/20 immersive visual display for simulation and Distributed Mission Operations (DMO). The technology driving the increased resolution of this display device is the Grating Light Valve (GLV) spatial light modulator developed at Silicon Light Machines in San Jose, CA. The GLV is a high-speed linear array, parallel scan micro-electro-mechanical system (MEMS) device that is currently capable of scanning up to 5120 x 1024 images. An Ultra GLV capable of scanning 5120 x 4096 pixel images is in development for an AFRL and Air Combat Command (ACC) Advanced Technology Demonstration (ATD) in 2005. Light sources illuminating the GLV are red, green, and blue lasers. Additional information on this technology can be found in Winkler and Surber (2001). The laser projector offers very high resolution and excellent temporal qualities. The current size of the laser projector is too large for helmet mounted applications, however further development of laser illumination technologies, development of a color sequential device, and improved packaging over the next several years could permit the eventual design of an ultra-high resolution laser display based HMD. Similar technologies are under development at Kodak and the Institute of National Optics (INO).

Another promising display technology is the flexible flat panel. These displays are currently under development by a number of organizations (Crawford, 2004). A device of this type would offer numerous advantages over current display devices and would remove many of the technological hurdles limiting factors such as weight, field of view, and resolution. These devices would be self-illuminating thus avoiding the packaging limitations created by the requirement for a separate light source. Another substantial advantage is that the device would be flexible or moldable. Although collimating optics would still be required to produce an image that appeared to be at a distance from the observer, the image source could be shaped for a curvature best fitting the requirements of the collimating optics. The elimination of the light sources would also reduce the weight and size of the device.

Another technology that would not require a separate light source is the organic-light-emitting-diode (OLED) display. These devices consist of a thin transparent layer of organic semiconductors or polymers, typically sealed between two substrates, usually glass or plastic. The front electrode of an OLED display is transparent and the rear electrode is reflective. Applying a voltage across the electrodes causes the organic layer to emit light (Post, 1999). It therefore does not require a separate light source,

simplifying weight and configuration concerns. These devices have been limited in their light output, response time, and resolution, but are making significant advances. OLED displays are already beginning to appear in a variety of products such as cell phones and PDAs. An OLED display of sufficiently high resolution, brightness, and decreased response time would be a prime candidate for use in a HMD.

A novel approach for potentially producing a wide field of view visual display for deployable training applications is the helmet-mounted conjugate optical system (CODS), a retro-reflective display system. This system is described in Geri, Arrington, and Miller (1999) and an initial analysis of technical and perceptual issues is presented. Briefly, this system consists of a head-mounted display that projects an image in front of the observer via a head-mounted beam splitter. The imagery is then reflected from a screen coated with retro-reflective material located at some distance from the observer. The advantage of such a system is that it provides collimated imagery – that is the imagery appears to be located at some distance from the observer. The optics of the system described by Geri et al (1999) are also relatively simple compared to a typical HMD. A similar but lighter and more advanced display system, a helmet mounted projection display (HMPD), has been developed at the Optical Diagnostic and Applications Laboratory (ODA Lab) at the University of Central Florida. They have also tested and developed a variety of materials for the required retro-reflective surface. Additional description of this work is available at <http://odalab.ucf.edu/>.

For an image plane located farther away than the retro-reflective screen the appearance of the system is described as similar to that of looking through a window. The limitations of this system, however, are similar to that of currently available HMDs. A higher resolution and wider field of view is needed for an acceptable deployable display system. This requirement necessitates either a display with a substantially greater number of pixels or the tiling of multiple displays. Although the optics of the device described by Geri et al (1999) and the ODA lab may be simpler compared to currently available HMDs, a larger field of view would require larger beam splitters and, if tiled displays are used, additional light engines.

Optics

The optical elements used in HMDs serve to direct images from the display to the eye. Various types of optics have been developed and different types of optical designs result in varying trade-offs in weight, image quality, field-of-view, and light throughput. A considerable amount of effort and expense goes into the design, consideration, and selection of optical components for HMDs. The focus of this review, however, is on the perceptual difficulties that may be encountered during the use of HMDs in particular applications. For a more detailed description of various optical designs Velger (1998), and Melzer and Moffit (1997) offer good descriptions.

Head Tracking Systems

Most applications with HMDs will require the use of head trackers to update the position of imagery as the head moves. For OBS applications, the position of symbology may need to be moved and the position of an aiming reticle will need to be specified for targeting purposes. The speed and accuracy of position updates are therefore very important. In OTW applications the speed and accuracy of these updates is even more critical because any lag in the head tracking and image update will be immediately obvious to the observer.

Head-position tracking devices may measure 3 degrees of freedom or, more typically, measure six degrees of freedom (DOF) of head position, including three angular orientations of roll, pitch, yaw, and three linear positions of x, y, z (Velger, 1998, pp. 78, 143). Measurement of 3 degrees of freedom is sufficient for applications where exact positioning of imagery relative to head-movement is not required. However, this type of system may not measure head roll – cocking the head slightly to the left or right for example.

There are several types of head tracking devices. These include magnetic (A/C or D/C), electro-optical, acoustic, and inertial (or combinations of these). Electromagnetic trackers, use an electro-magnet to create a magnetic field. The location of a sensor, which is mounted on the helmet, can then be tracked as it moves through the magnetic field (Velger, 1998, pp. 147). Electro-optical trackers operate using remote measurement by camera of the positions in space of LEDs mounted on the helmet (Velger, 1998, pp. 158; Toker & Velger, 1991). Acoustic, or ultrasonic, trackers are based on time of flight or phase coherence, which measure distances between emitters and receivers to compute head position (Velger, 1998, pp. 165; Meyer, Applewhite & Biocca, 1992). These head trackers are commercially available from several sources. Intersense Inc. (www.intersense.com) manufactures the IS-900 6-DOF acoustic-inertial tracker, and the lesser expensive IS-300 3-DOF inertial tracker. Polhemus (www.polhemus.com) manufactures the Liberty A/C electro-magnetic 6-DOF tracker, the Patriot 6-DOF A/C electro-magnetic tracker, and the Fastrak A/C electro-magnetic tracker. Ascension Technology Corporation (www.ascension-tech.com) manufactures the LaserBird 6-DOF electro-optical tracker, Flock of Birds DC magnetic 6-DOF tracker, and PCI Bird DC magnetic 6-DOF tracker.

The various types of head trackers have differing advantages and disadvantages. Generally, the more expensive systems will have higher update rates and may have more sensors for improved speed and accuracy (for example, the Polhemus Liberty has 8 sensors and an update rate of 240 Hz, the Patriot is a 2 sensor 60 Hz system). The sophistication of the motion prediction and noise filtering algorithms may also vary from system to system. Frequently, a Kalman filter is used to extrapolate head position several milliseconds ahead of time to improve head tracking (Velger, 1998). Additional sensors may also

be used for more accurate head tracking (Velger, 1998). The electro-optical trackers have less temporal lag than the electromagnetic trackers. Electro-magnetic tracking systems may also be affected by nearby metal objects and electromagnetic radiation (Ferrin, 1991). However, the electro-optical trackers require a direct line-of-sight and large field of view (Velger, 1998, pp. 80). Range of motion may also have some limitations depending on the placement of the LEDs and cameras. The ultrasonic trackers could potentially have problems due to contamination by external acoustic noise (Velger, 1998, pp. 165). The acoustic sensors also require very precise placement to maintain accuracy and likely require professional installation. Inertial trackers have the advantage that they are self-contained and do not require a separate signal source or sensor; however, they will have a slower response and may also tend to drift. Adding an acoustic sensor (such as with the IS-900) allows the inertial sensor drift to be corrected.

Anderson, Vrana, Riegler, and Martin (2002) evaluated several types of head-tracking systems for use with the Night Vision Training System developed at AFRL, Mesa and describe the conditions under which one type of head-tracking system may have an advantage over another. Inertial head trackers were recommended for enclosed areas where the placement of additional sensors is not possible. Optical head-trackers were recommended under conditions where no instruments, switches, or visual displays are located above the observers' heads, and in situations where it is not required that technicians need to work around the observer as they will block the optical sensors tracking the observers' head movements. Magnetic trackers were recommended if operating space is minimal. Magnetic trackers have an advantage over inertial because they provide orientation data (heading, pitch, roll) as well as X, Y, and Z coordinates. DC trackers may work better in cases where more metal is present. A magnetic map can be obtained for custom fits to the working area. If large pieces of metal are introduced following installation a new magnetic map may need to be generated to maintain the accuracy of the head-tracker. However, Vision Systems International (VSI, San Jose, CA, <http://www.vsi-hmcs.com/> - personal communication) has indicated that the magnetic head trackers are fairly robust and the introduction of relatively small metal objects does not significantly affect the accuracy of the head trackers used in conjunction with the Joint Helmet Mounted Cueing System (JHMCS).

To accommodate a wide range of training tasks the following ranges of head movements should be measurable with a head tracking system: angular azimuth (180 deg), elevation (130 deg), and roll (120 deg), with an accuracy of about 1-2 mrad on-bore sight and 2-6 mrad at 10 deg eccentricity, and linear displacements in the vertical (450mm), horizontal (400 mm), and fore/aft (540 mm) axes (Velger, 1998, pp. 144-145).

Off-Bore Sighting

Requirements for a device such as the JHMCS for training and simulation purposes may be quite different from those in the real aircraft. For example, in the aircraft, the brightness and contrast of the JHMCS needs to be great enough to produce imagery that is visible against a bright sky, which can be at levels on the order of 10,000 fL (Velger, 1998). This is not a requirement for simulation where luminance levels do not typically exceed 30 fL with current CRT-based rear projection imagery. However, similar contrast levels between the HMD symbology and background imagery in the simulator

relative to the real world would be desirable. For simulation purposes the OBS HMD would first have to be integrated with current visual displays used for display of OTW imagery as well as the computers used for sensor simulation, and aircraft orientation and motion in order to correctly model the designation of targets using the HMD targeting symbology and correctly update attitude, heading, and air speed symbology. Any head tracking lag, bore sight errors, or other difficulties that are present in the real JHMCS should be duplicated for training purposes in the simulated system. These issues may impose some unique engineering and integration challenges. However, our focus here will be on the perceptual difficulties that may be encountered with the incorporation of this type of helmet-mounted device into a current visual display system, specifically the Mobile Modular Display for Advanced Research and Training (M2DART).

Perceptual Issues in Monocular HMD Applications

Depth of focus

The M2DART is a full 360 degree field of view faceted display system used for DMO training and development at AFRL, Mesa (see Wight, Best, and Peppler, 1998 for a full description). This display system consists of eight flat display screens, with imagery rear-projected (see Fig. 5). Because it is a faceted display system, the distance from the eye-point to the display screen varies as the observer's head turns. This variation in viewing distance may create visibility problems for either the HMD imagery or the simulated OTW imagery because the observer may not be able to focus, or accommodate to both images simultaneously. The HMD symbology, the simulated OTW imagery, or both, may be blurred. The extent to which blurring may occur depends on the depth of focus of the pilots or other users observing the HMD and rear-projected imagery. Depth of focus refers to the range of distances in image space within which an image appears in sharp focus, and is specified in terms of diopters. An analogous spatial interval, given in meters, is referred to as depth of field (Ogle & Schwartz, 1959). Depth of field can be calculated using the formula $D = 1 / F$, where D is depth of field (meters) and F is depth of focus (diopters). Objects varying in depth, such as variation in depth between the HMD and simulated OTW imagery, to an extent greater than a pilot or other observer's depth of focus will cause perceived blurring. In the M2DART, this variation can be as much as 19 inches if the focus distance of the HMD imagery is set equal to that of the nearest distance between eye-point and display screen.

A similar problem could be encountered with other faceted display systems, such as the VIDS available from The Boeing Corporation (<http://www.boeing.com/defense-space/aerospace/training/visual/visual.html>), the Simusphere available from L3 Communications (<http://www.link.com/products/simusphere.pdf>), or the WASP available from Glass Mountain Optics (<http://www.glassmountain.com/wasp.htm>). However, the variation in distance between image planes

will differ on each of these systems. The greater the distance between the HMD image plane and the simulated OTW image plane, the greater the potential for perceived blurring of the imagery. Difference in distance between image planes would not be an issue for a dome type display, such as that available from Barco (Barco Simulation Inc.), so long as the focal distance of the HMD is matched to the radius of the dome.

Other factors affecting depth of focus include the brightness and contrast of both the HMD imagery and the rear-projected simulated OTW imagery and display resolution. Display brightness will affect pupil size, which in turn will influence depth of field. A brighter adapting luminance will decrease pupil size and increase depth of field, thereby decreasing the likelihood of blurring of imagery on either display. For example, Ogle and Schwartz (1959) report that for each mm of increase in pupil size (ranging from 2.5 to 8.0 mm), depth of focus decreased by 0.12 diopters. Conversely, a greater degree of resolution will lead to a smaller the depth of field (Campbell, 1957; Ogle & Schwartz, 1959). Ogle and Schwartz (1959) showed that, using Snellen notation, for each step of increase in target resolution, the total depth of focus decreased by 0.35 diopters.

AFRL, Mesa conducted a study to determine whether or not depth of focus may be an issue for simulating a JHMCS type device inside a faceted display system such as the M2DART, as well as establish a focal plane distance for the HMD imagery that will minimize any blurring that may be present (Winterbottom, Patterson, Pierce, Covas, & Winner, 2005). The results of this study showed that depth of focus would not be an issue for displays with relatively low resolution. For displays with relatively high resolution (e.g., 1 arcminute/pixel) and the range of distances possible in the M2DART, however, it was possible to exceed depth of focus, causing some noticeable blurring of imagery. It was recommended that the focus distance of a monocular HMD integrated with the M2DART be set to the optical midpoint of the nearest and furthest viewing distances possible in the M2DART to minimize the potential for blurring when viewing the two displays simultaneously.



Figure 5. Air Force Research Laboratory's M2DART.

Accommodation-vergence mismatch

When viewing a see-through monocular HMD in a flight simulator, the stimulus to accommodation could be either the imagery of the HMD or the display screen of the simulator. The stimulus to accommodation could therefore be different than the distance to which the observer is verged. There are three possible effects of accommodation-vergence mismatch: (1) eye strain or visual discomfort; (2) blurring of HMD symbology or simulator imagery (affected by stimulus contrast and brightness); (3) misperceived size, depth, speed, and/or distance via the operation of perceptual constancy. On this latter point, it should be noted that perceived size, depth, and speed depends upon the visual system scaling or re-calibrating retinal size, retinal disparity, or retinal speed for changes in viewing distance, which is called perceptual constancy. To the degree to which accommodation and vergence provide the visual system with proprioceptive information about viewing distance, then changes in accommodation or vergence can affect perceived size, depth, or speed (see Patterson & Martin, 1992).

For example, consider the perception of size. When an observer moves closer to an object retinal image size increases, and in order for the observer to correctly perceive that the object's actual size did not vary (which is called size constancy), the visual system likely combines information about visual angle and viewing distance (Foley, Ribeiro-Filho, & Da Silva, 2004). For example, Peli (1990) notes that the perceived size of imagery on a monocular, occluding, HMD appears to change depending on the distance of the surface for which the opposite eye is accommodated. Wetzel, Pierce, and Geri (1996) varied viewing distance for alternately presented stimuli and asked observers to adjust the size of the comparison stimuli so that the two were equal. They found that stimuli presented at a near distance were generally

judged to be roughly 15-20% smaller than stimuli presented at the far distance. Measurements of vergence angle and accommodation taken during the observers' judgments of the size of the stimuli indicated that change in vergence angle was strongly related to the change in perceived size.

Consider also the perception of stereoscopic depth, which is the perception of depth based upon binocular parallax (also called binocular disparity). When an observer moves closer to a set of objects that vary in depth, binocular disparity increases. In order for an observer to correctly perceive that the actual depth relations among the stimuli did not vary (which is called depth constancy), the visual system likely combines information about binocular disparity and viewing distance (Patterson, Moe & Hewitt, 1992; Ono & Comerford, 1977; Ritter, 1977). An analogous phenomenon may occur with perceived speed. When an observer moves closer to a laterally moving object, the speed of the object's retinal image increases, and in order for the observer to correctly perceive that the actual speed of the object did not change (which is called speed constancy), the visual system may combine information about retinal speed and viewing distance. In this case, however, the existence of speed constancy is controversial. Some authors (Pierce & Geri, 1997; Wallach, 1939; Zohary & Sittig, 1993) have found evidence for speed constancy, at least under some conditions, but other authors (McKee & Welch, 1989) have not.

Misaccommodation may in fact be a common occurrence when viewing virtual displays superimposed upon a real scene or a secondary displayed image. Edgar, Pope, and Craig (1993), for example, reported that many observers tended to misaccommodate when viewing virtual displays superimposed upon a real scene. In this case, the virtual imagery consisted of text lettering projected monocularly in front of the observer via a beam splitter (a condition similar to that which may occur with monocular OBS). Observers' accommodative state was measured using a laser optometer as they viewed a distant building through a window. Accommodative state was measured while observer viewed only the building through the window, and when both the text and building were viewed. The results indicated that observers' accommodative state tended to drift towards the resting state, away from infinity focus, when both the text and building were viewed. Edgar, Pope, and Craig also go on to comment that such misaccommodation may lead to misperceived size and distance.

In summary, with monocular HMDs there is clearly a potential for a mismatch between accommodative demand and vergence. The most likely symptom of this mismatch is eyestrain or visual discomfort. Misperceived size, distance, or speed may also occur. These effects could have some training effectiveness implications so it is important to determine whether these conditions occur when a monocular HMD is integrated with another display system for training applications. Minimizing the difference in distance between HMD focus distance and the OTW imagery plane may minimize the potential for this mismatch.

Binocular rivalry

With see-through monocular HMDs, synthetic symbology is presented to one eye of the user via the HMD, and the other eye views a synthetic or real-world scene, thus interocular differences may be created in brightness, contrast, color, flicker, shape, and accommodative demand (Velger, 1998, pp. 25). When the two eyes view different images, a condition known as binocular rivalry may ensue. Binocular rivalry is generally defined as a state of competition between the eyes such that one eye inhibits the visual processing of the partner eye. The visibility of the images delivered to the two eyes fluctuates during rivalry and the images projected to the two eyes rarely are visible at the same time.

Hakkinen (2003) states that monocular HMD displays produce a common problem of rivalry and perceptual instability and should be used only briefly (1-5 minutes). However, this finding is for occluding monocular displays, where each eye is viewing completely different imagery. Peli (1990) also documented the occurrence of binocular rivalry for an early version of a monocular occluding HMD. Hershberger and Guerin (1975) documented the occurrence of rivalry during the use of a monocular HMD with low transparency (10%). The results of their study suggested that ambient scene complexity, HMD resolution, HMD luminance, HMD accommodation distance, and ambient scene luminance were significant factors contributing to the occurrence of rivalry.

For applications where the monocular HMD is see-through with a high degree of transparency however, it is unclear at this point whether binocular rivalry occurs to a significant extent. This is the case for the JHMCS, where the left eye views the OTW scene (whether real or simulated) while the right eye views both the HMD imagery and the OTW scene combined. This is also the case for the Integrated Helmet and Display Sighting System (IHADSS), which has been used in the AH-64 Apache since the 1980's. It is similar to the JHMCS in that imagery from a CRT is projected onto a partially reflective piece of glass in front of the pilot's right eye. This allows the pilot to view both the outside world and the IHADSS imagery simultaneously in the right eye. Pilots can view symbology as well as Forward Looking Infrared (FLIR) imagery using the IHADSS (Behar et al, 1990).

The potential for binocular rivalry and significant visual discomfort during extended use of the IHADSS was a major concern so a number of AH-64 pilots were interviewed and tested before, during, and after use of the IHADSS (Behar et al, 1990). The results of the study indicated that a large percentage of pilots reported at least one visual complaint associated with flying an IHADSS equipped aircraft. Complaints consisted of visual discomfort, headache, double vision, blurred vision, disorientation, and afterimages. Of pilots complaining of visual difficulty the most common problem was blurred vision in right eye and/or headache. Twenty percent of pilots reported afterimages, particularly after viewing FLIR imagery in the HMD after long flights. About 70% of pilots noted that vision

occasionally and unintentionally alternated between their left and right eye either during or after flight. A few pilots also reported “browning” or “brown outs” in the right eye following usage of the IHADSS for long periods of time.

An analysis of the diopters settings, the focusing corrections set by the pilots while using the IHADSS, indicated that the settings were incorrectly adjusted and ranged from 0 to -5.25 diopters, with a mean of -2.28. These incorrect focus settings would cause significant eyestrain and discomfort during extended use. Behar et al therefore concluded that the source of the pilots’ visual complaints could therefore likely be attributed to incorrect focus adjustment, which could be corrected with proper training, rather than the occurrence of binocular rivalry. Nevertheless, the potential for rivalry was not ruled out. The simultaneous viewing of the real world and FLIR imagery, particularly at night, could create conditions conducive to rivalry due to the significant difference in brightness, contrast, color, flicker, and shape of the imagery in the two eyes.

In another study, it was concluded that transparent monocular HMDs may not be suitable for use under conditions where the background (OTW) scene is complex and dynamic (Laramée & Ware, 2002) due to the occurrence of binocular rivalry. The drive to display more information to pilots of fixed wing aircraft will create similar conditions. FLIR and other sensor imagery may find its way into devices like the JHMCS. For example, the HMD to be incorporated in the JSF is being designed to display imagery from various sensors in addition to symbology. It is therefore important to determine the parameters of the monocular HMD that minimize rivalry and visual suppression, as well as any other sources of visual discomfort, and establish longer periods of effective use.

Basic Research on Binocular Rivalry

To establish a foundation for future research on binocular rivalry a brief review of previous research follows.

Binocular rivalry has been shown to occur when completely different images are displayed to the two eyes (see Figure 6). For example, a grid of vertical bars shown to the left eye, and a grid of horizontal bars shown to the right eye will produce rivalry. Differences of luminance and color between the two eyes have been shown to induce rivalry (LeVelt, 1965). Reversed contrast imagery in the two eyes will also produce rivalry. Differences in brightness may produce the appearance of a polished surface. Rivalry induced by color difference is difficult to obtain and only arises in carefully controlled conditions. In those cases the two different colors, presented separately to the two eyes appear to fuse into a color that is the mixture of the two separate colors.

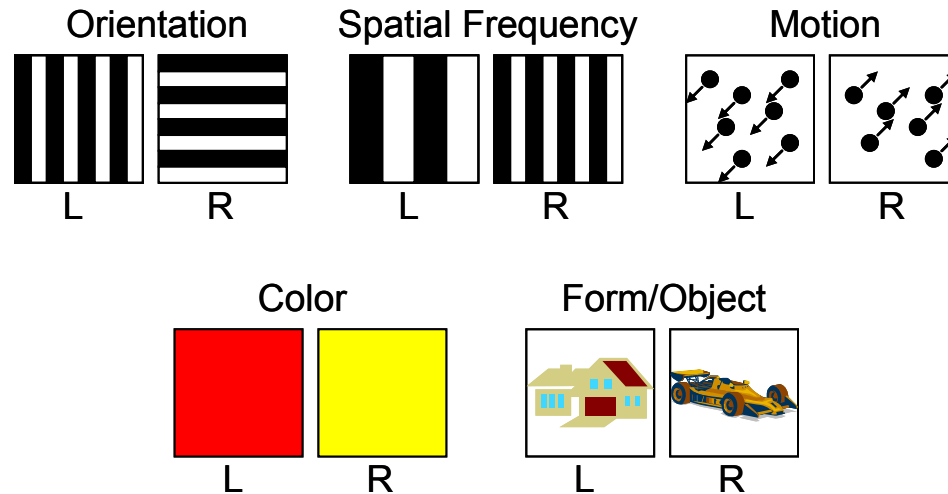


Figure 6. Conditions producing binocular rivalry.

LeVelt (1965) makes a distinction between two different forms of rivalry: true interactive rivalry and spurious rivalry. Interactive rivalry is the suppression of color, contour, or brightness in one eye by the stimulation of the other eye. Spurious rivalry occurs when a homogenous field is presented to one eye and a contoured target is presented to the second eye. The contoured target will dominate when viewed centrally, but will fade when viewed peripherally (despite the fact that contours generally dominate under these conditions). During spurious rivalry then, fixated targets will likely maintain visibility but targets in the periphery may periodically fade from view. LeVelt contends that this peripheral fading of imagery is not due to interactions between the two eyes but rather spontaneous fading of imagery referred to as Troxler's effect. This effect can also occur during binocular presentation. True interactive rivalry must therefore involve more than a homogenous field in one eye (i.e., contour-contour rivalry, color-color rivalry, etc.). Interactive rivalry and spurious rivalry may occur simultaneously however (LeVelt, 1965). Whether spurious or interactive, portions of presented imagery may disappear.

If images of two different luminance levels are presented to each eye separately the resulting percept will be intermediate between the two luminance levels and is referred to as brightness averaging. If the observer closes one eye to look only at the brighter field, he/she perceives a brighter image compared to the perceived brightness with both eyes open. This perceived decrease in brightness despite the fact that the total energy delivered to the two eyes is greater than that of the single brighter image seen by one eye is referred to as Fechner's paradox. In a series of experiments LeVelt shows how fields of differing luminance presented to the two eyes are weighted, and further, shows the effect of the presence of contours in one eye or the other on perceived brightness. LeVelt concludes that the effect of contours is a local effect, concentrated near the contour (as opposed to affecting brightness perception across the

whole eye), and that this mechanism is what leads to alternate fading between the left and right eyes in a more complex scene with more extensive contours combined with eye movements. The alternation of dichoptically viewed stimuli can be described by frequency and dominance. Frequency refers to how often the left and right images seem to alternate to the observer, while dominance refers to the total time that the left and right images are visible to the observer. Dominance and alternation have been found to be influenced by differences in contrast and stimulus size – or what LeVelt refers to as amount of contour per area.

Yang, Rose, and Blake (1992) note that a variety of perceptual states may occur during dichoptic viewing. One state is monocular dominance where the image presented to one eye is entirely visible and alternating with the complete image in the other eye. A second state is a mosaic consisting of portions of each image presented separately to the two eyes. A third state is the appearance of superimposed images that appear to be at the same depth. Yang et al refer to this as superimposition. A fourth state is similar to superimposition except that the two images appear to be at different depths and is referred to as transparency. Yang et al found that monocular dominance tends to occur when the two competing images are of similar, and generally lower, spatial frequencies. Superimposition was found to occur when the two images were of similar but higher spatial frequency. Transparency was found to occur more often when the spatial frequencies of the two images were significantly different from one another and when one of the images had a high spatial frequency. The spatial frequency content of the two images therefore influence the observer's resulting perception.

It has generally been assumed that binocular rivalry arises due to conflicting input from the two eyes. In other words, the conflict occurs early in visual processing due to two conflicting images from the two eyes. However, several researchers (Logothetis, Leopold, & Sheinberg, 1996, Kovacs, Papathomas, Yang, & Feher, 1996) have shown that rivalry might be thought of as two “conflicting stimuli” rather than “conflicting eyes”. In other words, the conflict may occur late in visual processing, at cortical levels. Binocular rivalry might therefore be similar to other bistable stimuli (such as the figure or ground alternation). Logothetis et al (1996) alternated rivalrous stimuli and compared dominance in this condition with typical static binocular stimuli. They found that a dominant stimulus could remain dominant even though it had switched from the “dominant eye” to the “non-dominant” eye. Kovacs et al (1996) compared typical static rivalrous stimuli with stimuli that had been broken into sections and swapped between left and right images. They found that observers effectively reassembled the broken images presented separately to the two eyes. Furthermore, frequency of rivalry alternation remained equal between the two conditions. This could not occur if rivalry was simply the result of the suppression of one eye's input over the other. These findings imply that imagery presented separately to the two eyes

may be less likely to provoke rivalry if they can be thought of as forming a complete percept, for example if one half of a face were presented to the left eye, and the other half to the right eye, observers may simply meld the two without significant alternation, or competition between the two images.

In support of this, it has been shown that neurons in the brain early in visual processing do not exhibit responses indicative of rivalry (alternating levels of activity). Recordings of the activity of neurons farther downstream (in the cortex), however, do show evidence of alternating patterns when two different images are presented to the two eyes (Blake & Logothetis, 2002).

Ocular Dominance

Related to binocular rivalry is the concept of ocular dominance. This refers to a person's preference for input from one eye or the other. Ocular dominance has been tested in numerous ways. Porac and Coren (1976) identified eight tests of dominance, which include sighting tests, unconscious sighting tests, binocular rivalry tests, acuity tests, motoric efficiency tests, clarity tests, perceptual efficiency tests, and measurements of innervation density. Coren and Kaplan (1973) performed a factor analysis on data from a battery of 13 tests for ocular dominance. The results indicate three factors to be most important: sighting, sensory, and acuity dominance.

Sighting dominance: These tests seek to observe which eye is consistently favored during monocular viewing tasks (such as when looking through a telescope). Many variations of this test have been proposed (Crider, 1944; Coren & Kaplan, 1973), some of which are designed to negate any effect of hand dominance by requiring participants to hold the sighting apparatus with both hands (unconscious sighting tests, Miles, 1929, 1930; Gronwall & Sampson, 1971). Sighting tests are simple to perform – a test that your optometrist may use during an eye exam simply involves forming a triangle with two hands and looking through the center of the triangle at a target on the wall. The target is then viewed alternately with one eye, then the other while the opposite eye is closed. The eye that is most in line with the target is identified as the dominant eye. When viewing the target through the triangle, if the dominant eye is closed to view the target with the other eye, the target will appear to shift to one side. For example, if a person is left eye dominant and then closes the left eye to view the target centered in the triangle with the right eye, the target will appear to shift to the right. This test is similar to the “hole test” described by Coren and Caplan (1973).

Due to their relative simplicity, sighting tests seem to be the most common test for ocular dominance. In addition, the results for sighting dominance, compared to other forms of dominance, appear to be the most reliable (Porac & Coren, 1976). Right-eyed sighters have shown more consistency in their preference than left-eyed sighters (Friedlander, 1971; Porac & Coren, 1975). Not only are right-eyed sighters more consistent, but they seem to be more numerous. Estimates from a variety of studies

indicate that about 60 – 70 % of the population are right-eyed sighters while 30 – 40 % tend to be left-eyed sighters (Porac & Coren, 1976).

Sensory dominance tests seek to observe which eye's input is favored longest during binocular rivalry tasks. This type of dominance has received far less attention than sighting dominance. However, like sighting tests, binocular rivalry tests have shown a preference for the right eye (Cohen, 1952; Coren & Kaplan, 1973, Porac & Coren, 1976). Some of the difficulties in this approach are that the results may vary depending on the size, color, contrast of the stimuli (Mapp, Ono, & Barbeito, 2003). One method of testing sensory dominance was developed by Washburn, Faison, and Scott (1934). Their method involves red and blue cards. Observers view the cards through a stereoscope, such that one card is visible to the right eye, and the other card is visible only to the other eye. The observers are then asked to indicate which color they see and when the color changes (i.e., red, blue, or purple). The experimenter simply records the time for which each color is dominant. LeVelt (1965) describes a similar method in which equibrightness curves are computed based on brightness matches between a test field presented to one eye and a separate field, which the observer can adjust, presented to the other eye. The slope of the resulting function indicates eye dominance. Behar et al (1990) used a relatively simple technique to assess eye dominance in which an observer viewed moving bars displayed on a monitor. A prism was placed in front of one eye so the direction of motion was different for that eye. The perceived direction of motion was recorded over time thus establishing eye dominance.

Acuity measures of dominance simply involve testing each eye separately for acuity. The eye with the best resolving power is identified as the dominant eye.

Sighting tests of dominance are clearly the easiest to perform and are the most frequently administered. The relative prevalence of right-eyed sighters is evident and current monocular HMDs such as the JHMCS are typically mounted over the right eye. However, the various tests for ocular dominance are generally not correlated (Mapp, Ono, & Barbeito, 2003). A sighting test may indicate right eye dominance for example, while a sensory dominance test indicates that either the left eye is dominant or neither eye is dominant. Dominance identified using sensory dominance tests may even vary depending on the type of stimuli used (e.g., dominance evoked with contours may be different from dominance evoked by color). It is therefore unclear at this point what significance measures of eye dominance have or whether they can predict anything about performance during the use of HMDs.

Out-the-Window (OTW) Viewing

We consider here the situation of using binocular HMDs for providing the OTW simulated imagery for flight training purposes. This simulation can involve either a real HUD and cockpit seen

through a semi-transparent HMD depicting an out-the-window scene, or the HMD imagery simulating both a virtual HUD and an OTW scene. In the latter case, an occluding HMD may also work, provided there is ample look-under clearance to view cockpit instruments.

When simulating OTW viewing, one can use either a biocular HMD or a binocular HMD. Biocular HMDs present the same imagery to both eyes of a user. Depth and distance would be conveyed by monocular cues such as perspective and motion parallax presented to both eyes with zero binocular parallax. Binocular HMDs present similar imagery to the two eyes of the user with binocular parallax between the views, which is achieved by presenting each eye's view from a different eye point. Depth and distance would be conveyed by monocular cues together with binocular parallax.

Ideally an HMD designed for display of simulated imagery for OTW viewing for training applications would be lightweight, un-tethered, have a large field of view equal to the field of view of the human visual system, eye-limited spatial resolution, and full binocular overlap for depth perception. In reality, however, each of these factors will trade off with one another, and the combination of all these characteristics is currently unachievable. For example, current light modulators are generally limited to about 1280 x 1024 pixels. If eye-limited resolution is a driving factor, the field of view is therefore necessarily limited to approximately 20 degrees per eye (i.e., 1 arcmin per pixel). If field of view is the driving factor the weight and size of the optics becomes an important consideration. As field of view increases, the weight and size of the optics required increases rapidly, while resolution decreases. Melzer and Moffitt (1997) and Velger (1998) discuss these important design issues in greater depth. Reducing the amount of cabling used to provide imagery and power to the HMD is also very important. For example, a significant complaint in an evaluation of the CAE advanced fiber-optic helmet-mounted display (FOHMD) was that the thick fiber optic bundles inhibited head movement (Brown et al., 1996). It is not currently possible to remove the cabling entirely but it may be possible to transmit imagery via a thin, lightweight fiber-optic cable to reduce factors inhibiting head movements as much as possible. Overcoming these difficulties pose significant engineering challenges. However, we will once again focus here on the perceptual issues likely to be encountered in OTW HMD applications.

Perceptual Issues in OTW HMD Applications

Field of View

The field of view of an HMD is an important consideration when designing and implementing any given HMD system. Field of view is important for the obvious reason that, other factors being constant, a larger field of view will better simulate natural viewing. The visual field of the human visual system extends 200 deg horizontal by 130 deg vertical, with the central 120 deg being the area of binocular overlap (Velger, 1998, pp. 50). Wide fields of view can be created with relatively large optics

(and therefore increasing the weight of the system) or smaller eye relief (Velger, 1998, pp. 64-65). However, increasing field of view typically lowers display resolution because the same pixels are mapped to a larger display area as field of view is increased, which therefore decreases resolution (Fisher, 1994).

Field of view may affect perceived size and distance as well as heading performance. These effects include the underestimation of size and distance in the display and impaired visual cognition (Osgood & Wells, 1991). Brickner and Foyle (1990) report that heading control in a flight simulator was impaired when the field of view was 25 deg relative to a larger field of view of 55 deg.

Pilots testing HMDs for OTW viewing applications invariably prefer large fields of view and one would generally expect that performance on a wide variety of tasks should be negatively affected with a restricted field of view. However, research investigating pilot performance on various tasks has yielded mixed results and clear recommendations on minimum field of view for flight training applications have not been established. To shed some light on the effects of field of view in HMD OTW applications a review of the published vision research literature on this topic follows.

The visual system is anatomically subdivided into different visual pathways - the parvocellular and magnocellular pathways (Livingstone & Hubel, 1988; Schiller et al., 1990). The parvocellular pathway has connections from the central retina and project mainly to areas in the visual cortex (located in the occipital lobe toward the back of the head) that make up the cortical ventral stream. Areas in the ventral stream functionally analyze spatial pattern information. Cells in these cortical areas have a sustained and sluggish response and poor temporal acuity. Many cells in these areas respond to color information and they have fine spatial acuity for functionally analyzing fine detail and high spatial frequency information. In general, the parvocellular pathway is thought to be involved in the functional analysis of spatial pattern information for the purpose of identifying objects.

The magnocellular pathway, in contrast, has connections from the central and peripheral retina, and projects mainly to areas in the visual cortex that make up the cortical dorsal stream. Areas in the dorsal stream functionally analyze optic flow information for heading control (Peuskens, Sunaert, Dupont, Van Hecke & Orban, 2001), biological motion (Grossman, Donnelly, Price, Morgan, Pickens, Neighbor & Blake, 2000; Grossman & Blake, 2001), and they integrate vision with action (e.g., Yabuta, Sawatari & Callaway, 2001; Ts'o & Roe, 1995; Van Essen & DeYoe, 1995). Cells in these cortical areas have a transient response and high temporal acuity. Cells in these areas do not respond to color information and they possess poor spatial acuity; they functionally analyze coarse detail and moderate or low spatial frequency information. In general, the magnocellular pathway is thought to be involved in the functional analysis of motion information for the purpose of locating objects, determining spatial relations, controlling heading during locomotion, and processing spatial orientation.

In a recent book, Milner and Goodale (1996) make a further distinction between the two pathways. They claim that the parvocellular pathway is involved only in the representation of visual experience while the magnocellular pathway is involved in the completely separate process of priming action and motor control. This view implies that any information gleaned from research on visual judgments and reports would not necessarily generalize to actual sensory-motor control tasks. Their claim is quite different from the typical view of the two pathways, namely that the parvocellular pathway is involved in the functional analysis of spatial pattern information while the magnocellular pathway is involved in the functional analysis of motion information. In support of this notion, Richman, Stanfield, and Dyre (1998) found that heading performance differed for active control versus passive viewing. They also found that heading control was differentially affected by field of view for active control versus passive viewing. With a large field of view (90 degrees), observers performed a heading task with less error using active control. For a small field of view (30 degrees) however, errors on the heading task were larger for the active control task compared to the passive viewing task.

Turning back to the problem of employing HMDs with a restricted field of view, using a HMD with a restricted field of view would mean that stimulation would occur mainly in the central portion of the retinae of the two eyes. Although eye movements are usually possible with a HMD, it is likely that the user would spend much of the time looking in the forward direction. This, in turn, would mean that the parvocellular pathway, rather than the magnocellular pathway, would be predominantly activated. Under such conditions, an observer's ability to control heading during locomotion and to process spatial orientation might be compromised, as might be the sense of immersion.

For example, Allison, Howard, and Zacher (1999) investigated the effect of the size of the field-of-view on roll vection and illusory self-tilt in a tumbling room. These authors found that complete 360-degree body rotation (tumbling) and increased speed of self-rotation was perceived by most observers under a full field of view condition. For smaller fields of view, tilt or partial tumbling and slower speeds of self-rotation were perceived. When the field of view was 50 degrees, only about one-half of all observers reported tumbling at an intermediate speed. This suggests that a field of view of at least 50 degrees is needed for some sense of immersion, and that a very large field of view would be needed for a complete sense of immersion.

Similarly, Duh, Lin, Kenyon, Parker, and Furness (2001) found that research participants' ability to balance was increasingly impaired as field of view was increased. In this experiment participants stood inside a 3 foot dome while a variety of scenes were projected and oscillated. Pressure plates were used to monitor center of balance. Fields of view from 30 degrees to 180 degrees were tested. Surprisingly, postural stability did not plateau even at the largest field of view tested (180 degrees). This suggests that

a sense of total immersion would require a very large field of view, greater than 180 degrees. Subjective ratings of difficulty in maintaining postural stability did begin to plateau at approximately 120 degrees however. This may provide a more attainable goal for HMD designers while still providing a sufficient feeling of immersion.

Tasks requiring accurate sense of self-motion, or the positioning of an aircraft relative to other aircraft, such as during formation flying, may also require large fields of view. For example, Weikhorst and Vacarro (1988) found that maneuvers such as the aileron and barrel roll were performed significantly better by pilots in a simulator with a wide field of view (300 degrees horizontally), compared to limited fields of view (144 degrees and 36 degrees horizontally). They also found that accuracy in dropping bombs, in terms of meters to the target, improved when field of view was increased. These authors further noted that the flight paths of pilots dropping bombs in the limited field of view conditions were significantly different from flight paths in the wide field of view condition. Significantly reducing field of view might therefore have serious training implications. In another study examining pilot performance in conducting realistic tactical maneuvers while field of view was varied, Dixon, Krueger, Rojas, and Hubbard (1989) found that increased field of view reduced the number of trials to train a low-level flight maneuver as well as a 30-degree manual dive-bombing task. Based on the results, they recommended a minimum instantaneous field of view of 160 x 80 degrees for flight simulation training applications.

Experiments examining field of view (Kruk & Runnings, 1989) with the CAE fiber-optic helmet mounted display (FOHMD) did not find statistically reliable differences in performance during various low altitude flight tasks as field of view was varied (127, 107, and 87 degrees). However, the pilots all indicated that workload while performing maneuvers in the limited field of view conditions was substantially higher. A similar finding was noted for high altitude air-to-air combat maneuvers. Significant differences in maneuvering time were found for formation flying as field of view was decreased. Pilots in this study found it very difficult to maneuver within 6 feet wingtip to wingtip on the fingertip formation, and substantial pilot induced oscillation occurred in the reduced field of view conditions. The authors attributed this to lack of motion cuing, as well as the reduced horizon reference for the reduced field of view conditions.

Other studies examining field of view however often show a plateau at approximately 40 degrees. For example, in a study involving a simulated nighttime attack, Osgood and Wells (1991) examined size of the field of view for an aircraft-fixed sensor whose image was seen on a HUD and for a head-steered sensor seen on a helmet-mounted display. With the head-steered HMD system, and for larger fields of view, observers acquired the targets quicker up to a field-of-view of 40 degrees, beyond which performance did not significantly change. Kenyon and Kneller (1993) investigated the effect of field of

view on a visual tracking task and found that near-asymptotic performance was obtained with a field of view of only 40 degrees.

Generally, the difference between those experiments that find that a large field of view is beneficial and those that find that limited fields of view (less than 60 degrees) are sufficient is the type of task that is examined. Based on the hypothesis proposed above, performance of tasks primarily engaging the magnocellular visual processing system will benefit from a very large field of view (greater than 60 degrees), while those tasks primarily engaging the parvocellular visual processing system can be performed accurately with a limited field of view (less than 60 degrees). For example, formation flying, and basic combat maneuvers, such as barrel rolls, tasks that, in short, require accurate perception of self-motion (or simulated self-motion in this case), benefit from a large field of view. Targeting tasks, tracking tasks, and object recognition tasks, in contrast, are performed accurately with field of view as small as 40 degrees. Additional research should be performed with visual tasks chosen using this framework to establish a field of view for HMD applications that can support adequate performance for perception of self-motion while still maintaining feasible optical size, weight, and resolution. A concept that might be considered, for example, is a small field of view, high-resolution central area, with a low-resolution wide field of view surrounding area. This might provide the high-resolution detail necessary to support target identification without reducing the perception of optic flow or other cues necessary for the perception of self-motion.

Interocular differences

With binocular HMDs, the content of the imagery and scenes projected to the two eyes is usually different only in a way consistent with binocular parallax and rivalry usually does not ensue. When the content of the synthetic scenes delivered to the two eyes is the same or very similar, binocular fusion results. However, the content of imagery shown to each eye could vary considerably in practice. For example, designers could present symbology to one eye while both eyes view the OTW scene, in a manner similar to the JHMCS. As another example, FLIR imagery could be displayed to one eye while the other eye views the OTW scene. If these types of situations can be expected it will be important to determine characteristics of binocularly presented imagery that reduce the occurrence of rivalry. Additionally, slight interocular differences in certain image characteristics, which still allow fusion to occur, can nonetheless cause unwanted perceptual effects. For example, slight differences in line orientation between images delivered to the two eyes will create the perception of a line tilted through the Z-axis, as well as a cyclotorsion response (Pierce, Arrington, & Moreno, 1999). Over a period of time, this could create muscle fatigue and eye strain. Additionally, slight differences in the size of images can create the perception of an object rotated about the vertical axis.

With regard to visual tolerance for interocular differences in simulation using a binocular HMD, Rash, Mozo, McEntire, and Licina (1996) suggest that interocular differences in luminance of up to 30%, a rotational difference of up to 10 arcmin, horizontal or vertical differences in image size of up to 1.5%, and deviation between centers of the two displays of 0.18 prism diopters (6.12 arcmin), all should be acceptable.

Convergent and divergent partial overlap displays (see Figure 7) can produce perceptual conflicts such as luning, which is a form of rivalry in which there is a subjective darkening of the monocular regions near the border with the binocular overlap region (Velger, 1998). Luning can be minimized by reducing the luminance near the edges of the binocular region (Velger, 1998, pp. 56; Melzer & Moffitt, 1991; Klymenko et al., 1994; Grigby & Tsou, 1994). Luning may be related to interocular suppression affecting unpaired monocular images (called half-occlusions) which do not normally occur with occlusion in the real world (Nakayama & Shimojo, 1990). With binocular viewing, unpaired images in one eye undergo either visual suppression or are perceived with depth depending upon whether the stimulus arrangement has ecological validity in terms of occlusion. It is therefore important to determine whether problems with convergent versus divergent binocular displays are related to stimulus conditions that mimic occlusion (Nakayama & Shimojo, 1990); and whether one type of display may be better than the other in terms of less visual suppression in the non-overlapping portions of the field of view (see Rash, Mozo, McEntire, & Licina, 1996 for more discussion of luning). Klymenko et al (2001) found that convergent overlap reduced reaction times in a visual search task compared to divergent partial overlap. However, they also found that reaction times were significantly lower in the full overlap condition compared to either the divergent or convergent partial overlap conditions.

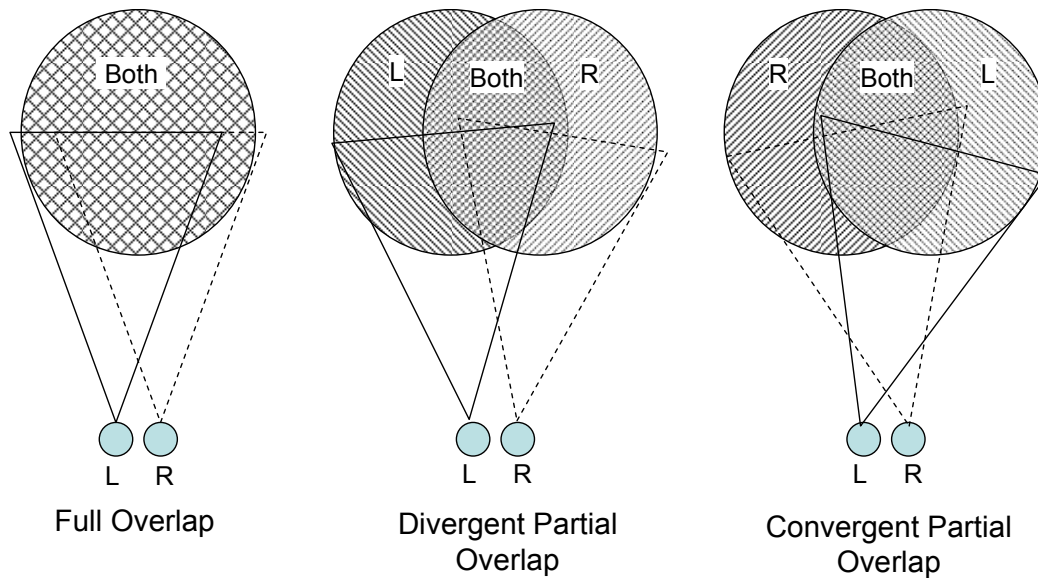


Figure 7. Binocular overlap conditions.

It will be important to determine how much binocular overlap is needed and assess its importance relative to field-of-view (field-of-view would necessarily have to be reduced to increase binocular overlap). For tasks where depth perception is particularly important, (e.g., a helicopter landing simulation), greater binocular overlap may be required and the subsequent reduction in field-of-view justified. Kruk and Longridge (1984) found that binocular presentation improved target detection for observers using the FOHMD compared to monocular presentation. However, they also found that target detection was degraded for targets located in a 5-degree lateral edge of the binocular overlap regions of the display (for both a 25 and 45 degree overlap). Because a greater percentage of the central viewing area would be subject to this reduced detection level for the smaller 25 degree overlap Kruk and Longridge recommended that an overlap greater than 25 degrees for subsequent HMD systems. Grigsby and Tsou (1994) state that binocular processing breaks down outside a 40-degree central visual region, so a central binocular overlap region of 40 degrees may be sufficient for many tasks if the observer is generally looking at the center of the displays. Furthermore, a 40-degree area overlap ensures that, for all but the largest eye movements, the fovea will remain inside the overlap area. Continuously crossing that boundary, and breaking and re-establishing binocular fusion, would likely result in fatigue during extended use (Grigsby & Tsou, 1990).

Although luning has been shown to affect performance for relatively simple static imagery it may be that the effect is less noticeable for more complex dynamic imagery. The complexity involved with designing a device with adjustable binocular overlap and vergence angle makes research into this issue difficult. However, additional research into this issue will be important to ensure important information is

not missed by an observer and how adjustments to combat luning may affect other factors such as field of view and eyestrain (see accommodation/vergence section below).

Accommodation/Vergence

For OTW viewing simulations, the display brightness and contrast should be sufficient for simulating the viewing of the outside world. The display brightness and contrast should be sufficient so as to minimize the tendency for accommodation to drift toward dark focus and at the same time produce a relatively large depth of focus so that images appear sharp and in focus despite the tendency to verge in a depth plane different from the display screen.

When simulating OTW viewing using a binocular HMD, the stimulus to accommodation would be the imagery of the HMD. However, when the user changes his or her vergence angle to view binocularly a virtual target in the synthetic scene, the vergence angle can be mismatched relative to accommodative demand. Recall that there are three possible effects of accommodation-vergence mismatch: (1) eye strain or visual discomfort; (2) blurring of imagery (depending upon stimulus brightness and contrast); and (3) misperceived size, depth, speed, and/or distance via the operation of perceptual constancies (Patterson & Martin, 1992). For example, Edgar, Pope, and Craig (1993) reported that observers tended to misaccommodate to virtual displays and may misperceive size and distance of objects, and Ellis, Bucher, and Menges (1995) reported that errors of judged depth of virtual objects are associated with variation in binocular vergence.

Lampton, Gildea, McDonald, and Kolasinski (1996) compared performance on several tasks while users viewed imagery through several different display types. One of the tasks they used was a distance estimation task. Distance estimates for a stationary object located 40 feet from the observer were compared for a binocular HMD, a standard computer monitor, and a boom mounted display. Real world performance was also assessed. Median responses for estimates while using the HMD were similar to the other conditions. However, the range of responses while using the HMD was substantially larger compared to the other display types and to the real world condition. Responses ranged from 6 feet to 300 feet. These results indicate that individual differences in distance scaling may indeed be substantial while using some HMDs. Judgments of size, speed, and depth may therefore also be affected.

A variety of configurations can be adopted for binocular HMDs. The vergence angle can be set so that: (a) the observer's eyes look straight ahead, (b) vergence angle is equal in depth relative to accommodative demand, or (c) vergence angle is set such that gaze angle overlaps (i.e., vergence condition similar to that of looking at a very near object) while accommodation may be at a greater distance. Figure 8 illustrates these conditions. Ideally, the configuration should be set in order to minimize eyestrain. Shibata (2002) found that eyestrain was least when vergence angle and

accommodative demand were matched in terms of distance. However, compromises may again need to be made in establishing accommodative and vergence configurations. Recall that Klymenko et al. (2001) found that a convergent configuration reduced the effects of luning to some extent in a visual search task. Furthermore, it may also be useful to consider dark accommodation when selecting focal length of the HMD optics.

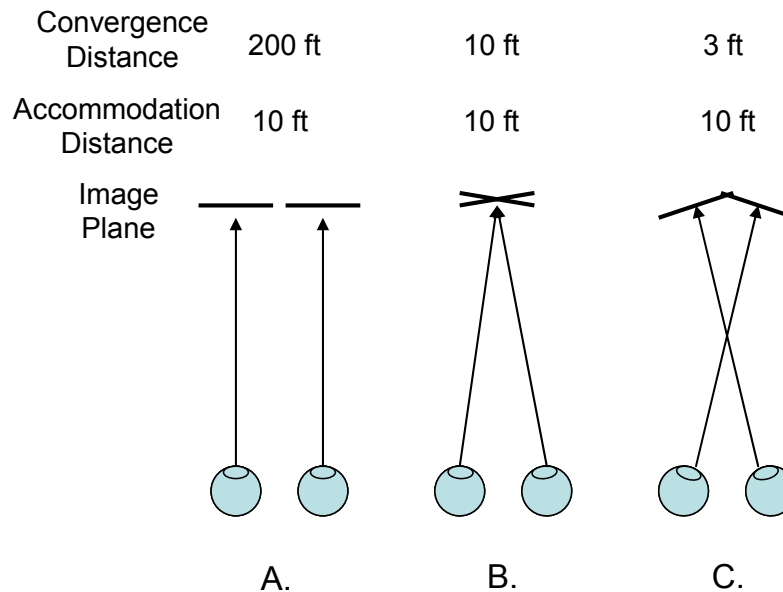


Figure 8. Accommodation and vergence conditions.

Head tracking lag

There are two perceptual frames of reference relevant to the discussion of HMDs: (1) environment-centered frame of reference (where the projection system is linked to the external world in terms of ambient light reflected off natural objects and surfaces); and (2) head-centered frame of reference (where the projection system is linked to the observer's head).

With an environment-centered frame of reference (i.e., viewing the world naturally), changes in eye or head position alter the pattern of retinal stimulation. With a head-centered perceptual frame of reference (i.e., viewing scenes projected on a helmet-mounted display), changes in eye position alter retinal stimulation but changes in head position do not. Changes in retinal stimulation that naturally accompany changes in head position must be simulated by computer and projected onto the HMD. For example, in the case of OTW viewing, the image on the display would be shifted with the same magnitude and in a direction opposite to the head motion. The shift of the visual scene would occur in a direction opposite to the head motion to mimic the shift in imagery that would occur within an environment-centered frame of reference.

Involuntary head movements occur when mission training or rehearsal occurs within an environment involving acceleration and/or vibration. In this case, involuntary head movements elicit a reflexive eye movement called the vestibulo-ocular reflex (VOR). The VOR entails involuntary eye movements which compensate for (i.e., are in a direction opposite to) the involuntary head movements so that fixation is maintained and the image is stabilized on the retina. For instance, if an individual's head vibrates upwards, the retinal image would slip downward, and the VOR would elicit a compensatory downward eye movement to maintain fixation on the object during the head movement. In an environment-centered frame of reference (real world), such a compensatory eye movement system is important for maintaining fixation on objects during locomotion (Benson & Barnes, 1978; Velger, 1998, pp. 207). Significant vibration would not be expected in most flight training environments, however, in shipboard training situations, such as on an aircraft carrier, involuntary head movements might be more of a concern.

With HMDs, which involve a head-centered frame of reference, compensatory eye movements (VOR) disrupt vision because, during the involuntary head movement produced by vibration, the retinal image moves with the head. The compensatory eye movements are inappropriate because they occur in a situation where head vibrations do not cause the retinal image to move (Lee & King, 1971; Velger, 1998, pp. 208, 232). This head vibration will cause visual performance to decline. For instance, acuity decrements and errors in aiming increase by a factor of 10 during head vibration (from an accuracy of 0.1 deg without head vibration to 1.0-1.5 deg with head vibration). The worst performance occurs at a frequency range of 3.2-5 Hz (Velger, 1998, pp. 216; Wells & Griffin, 1987, 1988). Below 1 Hz, users can make smooth pursuit eye movements to compensate (Huddleston, 1970; Velger, 1998, pp. 216).

One remedy for an inappropriate VOR response while wearing a HMD is to measure the involuntary head movements with a head tracker and shift the image on the display with the same magnitude, but in a direction opposite to the head movement (and in the same direction as the VOR). This method attempts to stabilize the retinal image and mimic viewing within an environment-centered frame of reference (Velger, 1998, pp. 225; Young, 1976). Because most head motions occur within the range of 2-10 Hz, the head-position measurement computations should be carried out at a rate of 120-240 Hz (Velger, 1998, pp. 227, 232; see Ljung, Morf, & Falconer, 1978; Merhav & Velger, 1991). However, this method is relatively inaccurate and may not always be capable of distinguishing voluntary head movements from involuntary head movements (Velger, 1998, pp. 224; Wells & Griffin, 1984, 1987).

Accurate measurement of head position is challenging because head movements may exceed angular velocities of several hundreds deg/sec and accelerations of up to several thousand deg/sec² (Wells & Haas, 1990). However, these values are at the extreme end of head movement velocities and

accelerations. For example, Rash et al. (1998) found that 97% of all head movements of AH-64 pilots were between 0 and 120 deg/sec. When measuring head movements, one important issue is the temporal delay and/or lag between actual head position and update of the displayed imagery (i.e., rendering latency). So & Griffin (1992) found that lags on the order of 80-100 msec between head movements and corresponding shift of displayed imagery produced sensory conflict between proprioception and visual information. This degree of temporal delay or lag can produce perceptual confusion, nausea, and disorientation when viewing a simulated out-the-window view (So & Griffin, 1992; Velger, 1998, pp. 145, 171). With sufficiently long temporal lags, the user's perception of anticipated flight path and vehicle yaw rate become impaired (Grunwald & Kohn, 1994). Moreover, Jagacinski and Flach (2003) note that phase lags set up a stability limit on the forward loop gain of a control system, with larger time delays producing decreasing range of gains that will yield stable control.

With long time delays, there may be no stable gain that produces a rapid head-tracker response and a proportional control system may not work (pp. 99). According to Keller and Colucci (1998), the lag between the image displayed and actual head orientation/position/location can be the greatest obstacle in creating effective HMDs. They recommended that for see-through augmented reality HMDs and targeting applications, the lag should be no greater than 16 msec. Padmos and Milders (1992) suggest that for immersive displays, the latency of update should be less than 40 msec. To achieve these values, one may need to increase the sampling rate or computation rate of head position, use a prediction algorithm to predict head position at some future point in time, or use auxiliary acceleration measurements (e.g., accelerometers or gyroscopes mounted on a helmet; Velger, 1998, pp. 172; Merhav & Velger, 1991). Olano, Cohen, Mine, and Bishop (1995) discussed techniques for combating rendering latency by making the rendering latency equal one NTSC field (1 video frame, or 16.7 msec for a typical 60 Hz frame rate) and by rendering the pixels in a scanned display based on position in the scan.

During head movements, users typically move their eyes as well as their heads such that the eye movement leads the head movement and there is an angular offset between eye orientation and head orientation (Velger, 1998, pp. 173; Robinson, Koth, & Ringenbach, 1976). Thus, more accurate measurements of line of sight are available when eye movements are measured as well as head movements (Velger, 1998, pp. 173). Some current eye trackers may operate at the speeds and accuracies required for an eye-tracked HMD. In a survey of current eye tracking technology (Latham, 2004) several eye tracker models were identified with accuracy of 0.5 degrees or less and a measurement delay less than 16 msec. However, many of these eye trackers were not suitable for use in combination with an HMD. Of the 11 eye-tracking manufacturers surveyed, only one was identified as having current eye tracking technology suitable for use in combination with an HMD. Two additional companies stated that HMD

compatibility could be achieved with some modification. The ability to integrate eye tracking with an HMD depends on the design of the HMD. For some HMD designs, it may not be possible to mount a sensor or light source in the correct position necessary for measuring eye movements. For purposes of simulating an environmental frame of reference with a head-centered frame of reference, the measurement of eye movements is not necessary because in both cases the pattern of retinal stimulation would change with an eye movement. Eye tracking may be useful for reducing image generator requirements through the use of an eye tracked high-resolution inset within a lower resolution background image. Reduction of IG requirements will be a significant issue for high-resolution displays, particularly when portability is a major concern. Latham (2004) determined that an electronically slewed inset using current eye tracking technology provided a feasible solution to reducing IG requirements. However, previous implementations of eye-tracked insets (mechanical rather than electronic) were generally not perceived to have been satisfactory (although an evaluation by Peters & Turner, 1992 indicated otherwise).

CURRENT HMD TECHNOLOGY

A large number of HMD products are currently on the market that range in price from hundreds of dollars to tens of thousands of dollars. Monocular HMDs, which are significantly less complex in comparison to binocular HMDs, cost substantially less than binocular HMDs. Table 1 below provides a list of a number of currently available HMDs, their manufacturers, as well as some specifications and pricing. This is not a complete list and a number of other manufacturers such as Sony, Canon, Olympus, etc. also make HMDs. A more complete list of HMDs, which includes both currently available devices and discontinued items, is maintained by Stereo3D at <http://www.stereo3d.com/hmd.htm#chart>. HMDs developed specifically for use in aircraft, such as the JHMCS (Vision Systems International) are also not listed here. These systems typically require specialized equipment and would require significant modification for use in simulation and training applications. The products that are listed require only standard VGA or DVI inputs and are therefore compatible with PC-based image generators (PC-IGs) commonly used for simulation.

Table 1. Commercially available Head-mounted displays in 2005. (All photos used with permission.)

Commercially available Head-mounted Displays (2005)						
Photo	Model	Manufacturer	Type	FOV	Display Type & Pixel Format	List Price
	ProView SR80	Kaiser Electro-Optics	Binocular, Occluding	63 degrees (H)/100% overlap	FLCoS, SXGA	\$27,000
	ProView SR100	Kaiser Electro-Optics	Binocular, Non-occluding (25% transmissive)	100 degrees (H)	FLCoS, SXGA	\$67,000
	ProView SO35	Kaiser Electro-Optics	Monocular, Occluding	28 degrees (H)	OLED, SVGA	\$8500/\$9500
	Advanced HMD	L3Communications	Binocular, Non-occluding (60% transmissive)	100 degrees (H)/30 degree overlap	FLCoS, SXGA	NA
	LiteEye 400	LiteEye	Monocular, Occluding	38 degrees	OLED, SVGA	\$1,599
	LiteEye 500	LiteEye	Monocular, Occluding or Non-Occluding	28 degrees	OLED, SVGA	\$2,895
	SV-6	MicroOptical	Monocular, Non-occluding	16 degrees (H)	LCD, VGA	\$1,995
	Nomad ND2500	Microvision	Monocular, Non-occluding	23 degrees (H)	Laser, SVGA	\$6,000
	nVisor SX	NVIS	Binocular, Occluding	60 degree (diagonal)/100% overlap	FLCoS, SXGA	\$23,900
	nVisor ST	NVIS	Binocular, Non-Occluding (50% transmissive)	50 degree (diagonal)/100% overlap	FLCoS, SXGA	\$34,900
	DataVisor80	nVision	Binocular, Occluding	120 degrees (H)/50% overlap	CRT, VGA or SXGA	NA
	DataVisor	nVision	Binocular, Occluding or Non-occluding	78 degrees (H) w/50% overlap; 52 degrees w/100% overlap	CRT, VGA or SXGA	NA

SUMMARY OF HMD CHARACTERISTICS

Table 2 below provides a summary of specifications for a monocular HMD integrated with the AFRL M2DART for OBS training applications. Table 3 below provides a summary of specifications for

a binocular HMD for deployable OTW training applications. These specifications are, wherever possible, based on the published literature related to perceptual issues and human factors research on HMDs. HMD characteristics of interest are listed in column 1 of each table. Minimum and desirable specifications are given in columns 2 and 3, respectively. The desired specifications do not necessarily reflect current engineering limitations for each of the characteristics listed but provide goals for technology development for HMDs. Minimum requirements are also quite stringent. However, many currently available, state-of-the-art HMDs approach the specifications listed in this column. These represent shorter-term goals for HMDs for the listed requirements. The final two columns of each table note whether each listed specification has been clearly established and whether additional technology development is needed to meet it. Additional advances in technology are required, for example, before a field of view matching that of the human visual system and a resolution of 1 arcmin/pixel can be achieved. Additional perceptual/human factors research may be needed to better define specifications that are noted as not clearly established.

Table 2. Specifications for monocular OBS HMD applications.

Monocular OBS HMD				
Characteristic	Desired Specification	Acceptable Specification	Clearly Established Criteria	Technology Development Required
Accommodative demand (focus distance)	Match to average distance (in diopters) of display screen: 0.905 diopters for M2DART ⁽¹⁾	Distance in diopters +/- 0.1 diopters	Yes	No
Ocular luminance difference	Isoluminance in left and right eyes	10-25% difference between left and right eye ⁽²⁾	Yes	No
HMD scene content	Unknown	Minimize occurrence of binocular rivalry [‡]	No	Unknown
Display luminance	70 fL*	30 fL**	Yes	No
Display Black Level	0.001 fL [†]	0.1 fL ^{††}	Yes	Yes
Resolution	Application dependent	Match to deployed equipment for training purposes	N/A	N/A
Field of View	Application dependent	Match to deployed equipment for training purposes	N/A	N/A
¹ Winterbottom, Patterson, Pierce, Covas, & Winner (2005); ² Self (1986)				
[‡] It is unknown at this time the extent to which rivalry occurs for these conditions or how specifically to mitigate against rivalry, however Hershberger & Guerin (1975) showed that ambient scene complexity, HMD resolution, HMD luminance, HMD accommodation distance, and ambient scene luminance were significant factors; * Expected M2DART maximum luminance with Laser Display; ** M2DART maximum luminance with CRT displays; [†] Approximate CRT black level; ^{††} Minimum expected OTW scene luminance				

Table 3. Specifications for binocular OTW HMD applications.

Binocular HMD				
Characteristic	Desired Specification	Minimum Specification	Clearly Established Criteria	Technology Development Required
Display Pixel Hold Time	< 1 msec*	< 8 msec**	No	Yes
Display Color Breakup	< 0.3 msec pulse duration ***	< 2.7 msec pulse duration ****	No	Yes
Refresh Rate/Update Rate	120 Hz ^{††(?)}	60 Hz ^{††}	No	Yes
Field of view (flight simulation/motion control)	200 degrees [‡]	127 degrees ⁽¹⁾	No	Yes
Resolution	1 arcmin/pixel ^{‡‡}	2.25 arcmin/pixel [‡]	Yes	Yes
Transmissivity	60%	50%	No	No
Vertical Misalignment	2 arcmin ⁽²⁾	5 arcmin ⁽²⁾	Yes [‡]	No
Horizontal Misalignment	0 divergence, 3.4 arcminutes convergence ⁽²⁾	3.4 arcminute divergence, 8.6 arcminutes convergence ⁽²⁾	Yes [‡]	No
Rotational Misalignment	0	3.4 arcminutes ⁽²⁾	Yes [‡]	No
Binocular overlap	40 degrees ⁽³⁾	> 25 degrees ⁽⁴⁾	No	Yes
Vergence/Accommodation imbalance	Accommodation matched to vergence angle ⁽⁶⁾	+/- 0.1 diopters ⁽⁶⁾	No	No
Eye Relief	50 mm	25 mm ⁽²⁾	Yes	Yes
Exit Pupil	15 mm	10 mm ⁽²⁾	Yes	Yes
System Lag (head tracker + IG)	< 16 msec ⁽⁷⁾	< 16 msec ⁽⁷⁾	No	Yes
Weight/ center gravity (cg) (including helmet or headband)	< 3 lbs with cg < 2 inches in front of y-axis of head ⁸	< 4 lbs with cg < 2 inches in front of y-axis of head ⁸	No	Yes
¹ Kruk & Runnings (1989); ² Self (1986); ³ Grigsby & Tsou (1994); ⁴ Kruk & Longridge (1984); ⁵ Shibata (2002); ⁶ Yeh and Silverstein (1990); ⁷ Keller and Colucci (1998); ⁸ Melzer & Moffitt (1997)				
*untested but based in part on data of Winterbottom et al (2004) may reduce motion blur by roughly 90%; **untested but based on data of Winterbottom et al (2004) may reduce motion blur by roughly 50%; ***untested but based on equation provided by Post et al (1998) should prevent noticeable color break-up for speeds up to approximately 160 degrees/sec; ****untested but based on equation provided by Post et al (1998) should prevent noticeable color break-up for speeds up to approximately 7 degrees/sec; †Partly an IG requirement, however refresh rate should match update rate (Lindholm & Martin, 1993); ††Current display refresh/update rate, display refresh rate should match IG update rate (Lindholm & Martin, 1993); ‡Matching field of view of human visual system; ‡‡Air Combat Command requirement; ‡HDTV resolution assuming current M2DART field of view; †However, may be based on optical systems other than HMDs (e.g. binoculars)				

In our view, both significant technology advances and additional perceptual research are needed, to develop an HMD for deployable, full field of view, OTW training applications. Although HMDs are one approach to developing a deployable OTW display for advanced aircraft simulation and training systems, user acceptance will be a critical hurdle and may depend on meeting all of the specifications

listed in the table, rather than just a few. Developing solutions to the limitations in current HMDs will require a solid understanding of many of the perceptual issues described in this report, as well as continued technology development in many of the areas described here and summarized in Tables 2 and 3.

FUTURE RESEARCH

In addition to several technology issues that are in need of further development (reduction of motion artifacts in digital displays, decreasing color break-up in field sequential displays, increasing display resolution, increasing field of view for near to eye applications, and decreasing head-tracking lag), there are also several perceptual issues that need to be resolved when attempting to simulate off-bore sighting or OTW viewing. These issues are the following:

(1) Binocular Rivalry. In simulating off-bore sighting, one eye views the HMD imagery and the simulator imagery combined while the other eye views simulator scenery alone. In this case, the existence of interocular differences in stimulus characteristics may produce binocular rivalry. It is important to determine whether rivalry occurs under these viewing conditions and, if so, determine what stimulus characteristics may reduce its occurrence. In simulating OTW viewing, the two eyes will view a binocular HMD that depicts an out-the-window scene of an ongoing mission. In this case, the existence of small, unintended interocular differences in stimulus characteristics may occur due to imprecision of mounting and alignment, which may produce rivalry or other unwanted perceptual effects. For example, it is known that small interocular differences in stimulus size can produce the perception of stereoscopic slant (Ogle, 1952). Additionally, it may be desirable to simulate both OTW viewing conditions and JHMCS type symbology using a binocular HMD. In this case, interocular differences conducive to rivalry may also be produced. It is therefore important to determine which interocular differences produce rivalry or other unwanted effects and whether training or practice can help mitigate such effects (for example see Rash, Mozo, McEntire and Licina, 1996 for a discussion of limits of interocular tolerance).

(2) Accommodation-Vergence Mismatch. When simulating off-bore sighting with a monocular HMD worn in a flight simulator, or simulating OTW viewing with a binocular HMD, the stimulus to accommodation will be the imagery of the HMD and/or display screen of the simulator. However, when the user changes his or her vergence angle to binocularly view a virtual target in the synthetic scene, the vergence angle can be mismatched relative to accommodative demand. There are three potential effects of accommodation-vergence mismatch: (1) eye strain or visual discomfort; (2) blurring of imagery (depending upon display brightness and contrast); and (3) misperceived size, depth, speed, and/or

distance via the operation of perceptual constancy. The effects of accommodation/vergence mismatch on visual discomfort, blurring of imagery, and perceived size, depth, speed and distance should be examined.

(3) Field of view. For simulating both off-bore sighting and OTW viewing, field of view can affect perception (e.g., perceived size, distance) as well as performance. This is because, in part, field of view determines the relative amount of stimulation of the parvocellular visual pathway (shape, fine spatial acuity, color perception) versus the magnocellular pathway (motion processing, location information). It is important to determine what size of field of view is needed and how that size will affect other important factors such as binocular overlap and resolution.

(4) Binocular overlap and convergent versus divergent displays. In simulating OTW viewing, it is important to determine the perceptual implications of using either convergent or divergent binocular displays. In particular, one should determine how the convergent versus divergent systems relate to half-occlusions, visual suppression, luning, and field of view, and whether one type of display is better than the other in terms of less luning or whether a full-overlap display should be considered. See Rash, Mozo, McEntire, and Licina (1996) for discussion of luning. However, it may be more important to match accommodative demand with vergence to reduce eyestrain (Shibata, 2002). For extended viewing conditions such as those encountered during simulation and training exercises, it will be important to reduce eyestrain and fatigue as much as possible.

(5) Head tracking of voluntary head movements. In simulating an out-the-window view, the display imagery must be shifted in a direction opposite to voluntary head and pursuit eye movements to mimic an environment-centered frame of reference. One problem is that the time required to measure the head movements with the head tracking system and update the display creates a temporal lag that impairs perception and cognition and also places constraints on the gain of the head tracking system (which potentially decreases the usefulness of the head tracker for measuring large voluntary head movements). It is therefore important to investigate the relationships among head-tracking accuracy, lag, and size of head movement so as to determine an acceptable set of parameters.

(6) Head tracking of involuntary head movements. If mission training or rehearsal utilizing an HMD is conducted in an environment that causes acceleration or vibration, the head will execute involuntary head movements that, in turn, elicit a compensatory and opposite VOR eye movement. The VOR eye movement impairs viewing of the HMD because the image moves with the head, which renders the VOR response as inappropriate. One approach for correcting inappropriate VOR responses while wearing an HMD is to measure the involuntary head movements with a head tracker and shift the image on the HMD by the same magnitude and a direction opposite to the head movement (and in the same direction as the eye movement). However, a difficulty with this technique is that the head tracker may

not be accurate enough to fully compensate for the VOR response. It is therefore important to determine to what degree HMDs will be used for mission training and rehearsal in environments involving acceleration or vibration. If those conditions are anticipated, then the relationships among head-tracking accuracy, lag, and size of head movement should be investigated so as to determine whether small (involuntary) head movements can be measured with an acceptable degree of accuracy and lag.

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APPENDIX

ACC	Air Combat Command
AFRL	Air Force Research Laboratory
AMLCD	Active matrix liquid crystal displays
ATD	Advanced Technology Demonstration
CODS	Conjugate Optical Display System
CRT	Cathode Ray Tube
DLP	Digital Light Processing
DMD	Digital Micro-Mirror Display
DMO	Distributed Mission Operations
DOF	Degrees of Freedom
FLCoS	Ferro-Electric Liquid Crystal on Silicon
FLIR	Forward Looking Infrared
FOV	Field of View
GLV	Grating Light Valve
HMD	Head-Mounted Display
HMPD	Head-Mounted Projection Display
HUD	Head-Up Display
IHADSS	Integrated Helmet and Display Sighting System
JHMCS	Joint Helmet Mounted Cueing System
LCoS	Liquid Crystal on Silicon
LED	Light Emitting Diode
M2DART	Mobile Modular Display For Advanced Research And Training
OBS	Off-Bore Sight
MEMS	Micro-Electro-Mechanical System
OLED	Organic-Light-Emitting-Diode
OTW	Out the Window
PDA	Personal Digital Assistant
VOR	Vestibulo-Ocular Reflex
VRD	Virtual Retinal Displays