

17 GUIDELINES FOR HMD DESIGN

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Helmet-mounted displays (HMDs) have been in development since the 1960s. Now, almost five decades later, the technology has improved significantly; HMDs have made some inroads into commercial applications (Ellis, 1995; Kalawsky, 1993; Pankratov, 1995); their use has become standard within the military community for flight applications, training and simulation (Simons and Melzer, 2003); and they are rapidly expanding into military applications for the dismounted and vehicular-mounted Warfighter (see Chapter 3, *Introduction to Helmet-Mounted Displays*). Unfortunately, design guidance for HMDs has not kept pace. This is due in part to the rapid advances in enabling technologies (e.g., micro-electromechanical devices, microprocessors, emissive image sources, microdisplays).¹ However, it is mostly because HMDs are both engineering- and human-centered systems; whenever humans are a key system component, their complex sensory, neural mechanisms and their variability across the population makes the design of HMDs and the human-machine interface extremely challenging. This, in turn, makes universal design guidelines equally challenging.

This is not to imply that the design community has been negligent in the development of guidelines. In a 1972 symposium on visually-coupled systems sponsored by the U.S. Air Force System Command's Aerospace Medical Division held at Brooks Air Force Base, Texas, participants attempted to address many of the fundamental design issues for HMDs (Birt and Task, 1973). Hughes, Chason and Schwank (1973) provided an overview of the history and the known and potential psychological problems of HMDs and included an extensive annotated bibliography of relevant material on such issues as eye dominance, brightness disparity, helmet-mounted displays/helmet-mounted sights, retinal rivalry, and others identified during the 1972 symposium. Chisum (1975) expanded this discussion by presenting visual considerations associated with the head-coupled aspects of HMDs.

As a special subset of displays, HMDs are subject to the practices for display development in general, many of which are based on decades of human performance research. Two of the most comprehensive volumes are Farrell and Booth's (1984) *Design handbook for Imagery Interpretation Equipment* and Boff and Lincoln's (1988) *Engineering Data Compendium: Human Perception and Performance*.

HMDs are also a specialized class of displays called head-up displays (HUDs), defined as transparent, fixed location displays that present data without obstructing the user's view (Figure 17-1). Developed originally as gun sights for military aircraft, they have expanded into commercial aircraft (Steenblik, 1989) and recently have become an option in some automobiles (Oldsmobile Club of America, 2006). HUD guidelines concentrate mostly on symbology and related display criteria such as clutter, dynamic response and viewing comfort issues, and many of these criteria have a firm foundation in human factors and human perception (Prinzel and Risser, 2004; Ververs and Wickens, 1998; Weintraub, 1992; Wickens, 1997; Wickens, Fadden, Merwin, and Ververs, 1998). Two important reference books on HUDs are Wood and Howells' (2001) *Head-Up Displays* and Newman's (1995) *Head-Up Displays, Designing the Way Ahead*.

However, of the vast amount of research conducted over the last half-century, only four reference books have been written specifically for HMDs; and the first three of these focus on aviation applications only. The first

¹ Suggested reading on these enabling technologies is Brennessholtz, M.S., and Stupp, E.H. (2008), *Projection Displays*, John West Sussex, UK: Wiley and Sons.

book, *Head-Mounted Displays: Designing for the User* (Melzer and Moffitt, 1997), addresses HMD development for fixed-wing aircraft. It could be considered an engineering guide with its coverage of the traditional engineering design approach, but it also places a significant emphasis on the end user, addressing a wide array of human-centered disciplines required for the design of head-mounted virtual reality, industrial and military displays. Topics include optical requirements, lens designs, cybersickness, eye strain, head-supported weight,² stereoscopic imagery, anthropometry, and user acceptance. The book also introduces the potential of HMDs to serve as an interface for brain-actuated control functions, a concept explored in this volume (see Chapter 19, *The Potential of an Interactive HMD*).



Figure 17-1. Examples of head-up displays (HUDs): (left) a HUD in a fighter cockpit and (right) a HUD designed for aircraft simulation (Rockwell Collins).

Melzer and Moffitt's book was quickly followed by *Helmet-Mounted Displays and Sights* (Velger, 1998) that is described by its author as "an in-depth, design practitioner's study of helmet-mounted display and sight technology (HMD/HMS)." Velger's book discusses human factors associated with the use of HMDs and details image source and display technologies. It offers practical recommendations for evaluating various optical designs and technologies, selecting appropriate image sources and displays, and applying the human-centered design concepts to helmet display systems. The book also provides insight into head-tracking systems and techniques for stabilizing display images, examining the effects of aircraft vibration on HMD effectiveness.

The third aviation-oriented HMD book was *Helmet-Mounted Displays: Design Issues for Rotary-Wing Aircraft* (Rash, 2001). This book differs from the first two reference books in that it focuses on the use of HMDs in U.S. Army rotary-wing aircraft, emphasizing the important issues associated with interfacing HMDs with the U.S. Army aviator. Topics include optics, vision, acoustics, audition, biodynamics, safety, ergonomics, and visual human factors.

While these three books are aviation-focused, the last of the HMD-specific books (National Research Council, 1997) is the end product of a special panel, *Human Factors in the Design of Tactical Display Systems for the Individual Soldier*, conducted by the Committee on Human Factors, National Research Council Washington, DC (National Research Council, 1995). This panel was established at the request of the U.S. Army Natick Soldier Research, Development, and Engineering Center (NSRDEC),³ Natick, MA, for the purpose "of explicating the human factors issues and approaches associated with the development, testing, and implementation of HMD technology in the (U.S. Army's) Land Warrior System." More specifically, the panel was charged with examining the relationship among tactical information needs of individual Warfighters; the possible devices available at that

² The terms *head-supported weight* (HSW) and *head-supported mass* (HSM) are used interchangeably.

³ Also known as the U.S. Army Natick Soldier Systems Center, Natick, MA.

time and in the near future for processing, transmitting, and displaying such information, and the human performance implications of the use of such devices.

In this chapter we summarize general guidelines and recommendations drawn from the references cited above (and others) that are useful in developing the “optimal” HMD design. In addition, we summarize the perceptual and cognitive principles presented in the previous chapters of this volume, and discuss design tradeoffs and their impact on system and human performance. However, the reader is cautioned that each HMD design is application and user specific. There is no single set of design criteria or guidelines that can be blindly followed. The designer must apply those guidelines that are best fitted to the desired design application and user population.

User-Centered Design Focus

The idea of a single optimal HMD design is an unobtainable goal. Simply stated, the concept of a one-size-fits-all HMD is a false one, primarily because of the wide variation in user tasks and users themselves; an HMD designed for the pilot of a fast fighter jet flying at 10,000 feet (3048 meters) will not meet the needs of a helicopter pilot flying close to the ground, and neither of these will meet needs of a dismounted Warfighter negotiating a brush-laden forest. Although there are some common design features – primarily driven by human perceptual and anthropometric limitations – across the various HMD configurations, many of the performance requirements and tradeoffs are user-, application- and environment-driven.

The following sections address the guidelines for HMD design while attempting to frame them in the context of a user-centric design process. It will become clear that there are a number of different configurations and tradeoffs available to the designer, each of which has advantages and disadvantages depending on the user’s characteristics and application. While significant breakthroughs have been realized in lightweight protective materials, optical design and fabrication, head/eye-orientation tracking, and miniature flat-panel image sources since Ivan Sutherland’s true HMD⁴, the following important questions must still be asked: “Who is the user?” and “What will he/she be doing with the HMD?” Once these questions are answered and key performance requirements identify, *suboptimizing* can begin. In doing so for the Warfighter, the minimum set of HMD features – separate from those of the protective helmet/platform – that are sufficient to allow the Warfighter to accomplish his mission without affecting his safety are identified. The beginning of the chapter emphasizes these minimum HMD features because the Warfighters’ mission and environment demands this suboptimizing process to simplify the design, reduce head-supported weight and drive down the cost. Thus, the recommendations in the following sections are best considered as a shopping cart of (often conflicting) advice, where the designer must make tradeoffs based on the specific environment, user population and application.

Design criteria, guidelines and recommendations are grouped and presented in the following sections for optical/visual, biodynamic, acoustic/auditory, perceptual/cognitive and user adjustment parameters.

⁴ Ivan Sutherland (1968) is credited with implementing the first virtual reality system. Using wire-frame graphics and a head-mounted display (HMD), it allowed users to visually occupy the same space as virtual objects. An even earlier head-mounted sighting system is described within the context of the historical pursuit for an accurate measure of longitude at sea (Sobel, 1996). In 1610, Galileo Galilei discovered the moons of Jupiter and soon concluded that knowledge of their precise position could give navigators at sea an accurate measure of Greenwich Mean Time (GMT) and therefore help determine their east/west location. In 1618, he designed a sighting system to aid in observing what are now referred to as the Galilean satellites. The navigator sat in a special gimballed chair designed to compensate for the motion of the ship and observed the moons with a *celatone*, a face-mounted device somewhat like a gas mask that held one, or possibly two telescopes. Though no drawings or models exist, it is interesting to be able to push back the invention of the earliest head-mounted display sighting system to one of the most brilliant inventors in history.

Optical/Visual Guidelines and Recommendations

The following optical/visual parameters and issues are addressed:

- Ocularity (monocular, biocular or binocular)
- Field-of-view (FOV)
- Resolution
- Pupil-forming versus non-pupil-forming optics
- Exit pupil and eye relief
- Optical distortion
- Luminance and contrast
- See-through versus non-see-through considerations
- Considerations for helmet-mounted sensors

Ocularity

Ocularity refers to whether the HMD provides monocular, biocular and binocular imagery as defined by:

- *Monocular* – a single image source is viewed by a single eye
- *Biocular* – a single image source viewed by both eyes
- *Binocular* – each eye views an independent image source

Moffitt (2008) further subdivides monocular and binocular HMD configurations⁵ into categories that focus on their respective applications (Table 17-1). The variety of monocular configurations is discussed first. If the HMD will be used to provide moving map or text information for a dismounted Warfighter, or to allow a pilot to view imagery with the simplest, lightest and least costly system, a monocular design is best. Variations include the Joint Helmet-Mounted Cueing System (JHMCS) for fixed-wing (F/A-18, F-16 and F-15) aircraft and the Integrated Helmet Display Sighting System (IHADSS) for the Army's AH-64 Apache helicopter (see Chapter 3, *Introduction of Helmet-Mounted Displays*). The AN/PVS-14 night vision goggle (NVG) and the SO35A for the Land Warrior program are also monocular. The single image source configuration reduces cost, head-supported weight/mass, power consumption and simplifies the opto-mechanical alignment requirements. There is the potential for a laterally asymmetric center-of-mass (CM)⁶ and issues associated with focus, eye dominance, binocular rivalry and ocular-motor instability (Moffitt, 1989; Rash and Verona, 1992), although these issues have not been shown to have an insurmountable impact on performance if the user is properly trained. Table 17-2 presents a summary of performance and ergonomic benefits and disadvantages of monocular optical designs.

Questions of how monocular HMDs interact with the dominant eye continue. Moffitt (2008) cites research (Mapp, Ono and Barbeito, 2003) that defines the dominant eye as the one that individuals use for monocular sighting tasks. This is the situation for Warfighters wearing the AN/PVS-14 NVG or the Land Warrior HMD, where they place the HMD or NVG over their *non-dominant* eye, leaving their dominant eye clear for weapon aiming.

To achieve the widest field-of-view (FOV) possible, the HMD must be either *biocular* or *binocular*. The biocular/binocular approach is more complex than the monocular design, but because it stimulates both eyes, it eliminates some of the visual rivalry issues associated with monocular displays and reduces cost because there is

⁵ Moffitt (2008) considers the biocular design to be a subset of binocular HMDs as “binocular HMD using a single display,” although they will be separated in this chapter for clarity.

⁶ The terms center-of-mass (CM) and center of gravity are used interchangeably.

only a single image source as in the case of the AN/PVS-7D NVG. Taxonomy of binocular HMD configurations with design considerations and examples is presented in Table 17-3.

Table 17-1.
Taxonomy of monocular HMD configurations, considerations and examples.
(adapted from Moffitt, 2008)

Designation	Description	Considerations	Example
Monocular HMD Configurations			
Compact offset	The compact offset monocular is positioned for brief viewing away from the user's forward line-of-sight. It is used for applications not requiring extended viewing.	Imagery is not in spatial correspondence with the outside world. May distract user from primary viewing tasks. Does not block forward line-of-sight, preserving binocular vision for motor and navigation tasks.	<ul style="list-style-type: none"> Rockwell Collins SO35A⁷ Sportvue[®] MC2⁸
Opaque	Similar to the compact offset, except the HMD is positioned directly in the user's line-of-sight. Provides only graphic or text information, it is not intended to present imagery that is overlaid on the outside world.	Better configuration for longer duration viewing, though with potential issues with binocular rivalry between viewing and non-viewing eye.	<ul style="list-style-type: none"> Eyetop[™] Centra⁹ Liteye Le-700A¹⁰
Video see-through	A head-mounted camera or sensor is used as one source of imagery in-line with the viewing eye.	Could distract user from other tasks with FOV that is smaller than the non-viewing eye. Camera and HMD need to be in corresponding alignment. If offset from eye line-of-sight, may create viewing artifacts.	
Optical see-through	Imagery superimposed over see-through view.	Reduced see-through in viewing eye may induce perceptual artifacts. Monocular viewing of imagery may rival outside world view.	<ul style="list-style-type: none"> IHADSS JHMCS

Viewing imagery with two eyes vs. one has been shown to yield improvements in detection as well as providing a more comfortable viewing experience (Boff and Lincoln, 1988; Moffitt, 1997). Table 17-4 presents a summary of performance and ergonomic benefits and disadvantages of biocular and binocular optical designs.

Since it is a two-eyed viewing system, the biocular design is subject to a much more stringent set of alignment, focus and adjustment requirements.¹¹ This generally has been deemed a difficult design for flight applications,

⁷ The Rockwell Collins' SO35A is the HMD used on the U.S. Army's Land Warrior program.

⁸ Motion Research Corporation, Seattle, WA.

⁹ Ingeineo, SAS, Villiers Le Bel, France.

¹⁰ Liteye Systems, Centennial, CO.

¹¹ For *absolute* horizontal alignment, in *non-see-through* HMDs, the binocular alignment is not critical as long as it agrees with the focus to within $\pm 1/4$ diopter. For *relative* horizontal alignment, in *see-through* HMDs, the horizontal binocular alignment must be within 5 to 10 arcminutes of the desired vergence distance and the focus must agree to within $\pm 1/4$ diopter.

For *absolute* vertical alignment, in *non-see-through* HMDs, the binocular alignment must be within 10 arcminutes. For *relative* vertical alignment, in *see-through* HMDs, the binocular alignment must be within 3 to 6 arcminutes (Boff and Lincoln, 1988; Moffitt, 1997; Self, 1986).

Table 17-2.
Human performance considerations of monocular optical design approaches.
(adapted from National Research Council, 1997; Melzer, 2006)

Ocularity	Human Performance, Sensory and Ergonomic Considerations	
	Benefits	Disadvantages
Monocular (one image source viewed by one eye)	<ul style="list-style-type: none"> • Minimum weight • Simplest HMD; less stringent alignment • Eye with no display remains dark adapted and continues to sample real world • Least expensive 	<ul style="list-style-type: none"> • Possible visual rivalry problems, such as target suppression (involuntary), “cognitive switching,” ocular-motor instability, eye dominance and focus issues • Asymmetric CM • Smallest FOV; least information capability; more and larger head movements required • No stereoscopic depth information • Difficult to navigate on uneven terrain

Table 17-3.
Taxonomy of binocular HMD configurations, design considerations and examples.
(after Moffitt, 2008)

Designation	Description	Considerations	Examples
Binocular Viewing Configurations			
Opaque	Provides completely occluded view of immersive synthetically-generated monoscopic or stereoscopic imagery.	Users are visually isolated from the real world. Potentially a safety hazard if users rely on this imagery for navigation.	MyVu <i>Personal Media Viewer</i> Daeyang <i>i-Vision</i>
Video see-through	Outside world imagery provided only through video camera(s)	Single camera provides monoscopic imagery. Separation of two cameras of greater than 2.5 inches can create hyperstereo imagery	Mirage <i>Augmented Reality System</i> Trivision <i>Scout 2</i>
Optical see-through	Video imagery is projected on a see-through combiner. Can provide geo-spatially registered imagery	Video overlay may confuse users as in the monocular see-through.	Rockwell Collins <i>SR100A</i> Rockwell Collins <i>JSF RSV HMD</i>
Extended Binocular Configurations			
Partial binocular overlap	Optical channels are canted inward (convergent) or outward (divergent) to increase the horizontal FOV	Critical binocular alignment requirements in the overlap region. Binocular rivalry possible in the unpaired binocular-monocular boarder region.	Rockwell Collins <i>SR100A</i>
Paneled or optically tiled	Individual display modules are optically “tiled” next to each other to enlarge the FOV	Difficult design in see-through. Overlap regions must be corrected for content, focus, distortion, alignment, color, and contrast.	Sensics <i>piSight</i>
Mixed resolution or dichoptic	Small FOV, high resolution image in one eye. Larger FOV, lower resolution image in other eye.	Image fusion using blur suppression is assumed. Ability of a wide range of users to fuse the images is not known.	DARPA’s <i>MANTIS</i>

because it requires two optical paths of equal length, which puts the image source in the middle of the head, generally high and forward. In addition, the display luminance is cut in half because the single image source is split in order to be presented to both eyes.

Table 17-4.
Human performance considerations of biocular/binocular optical design approaches.
(adapted from National Research Council, 1997; Melzer, 2006)

Ocularity	Human Performance, Sensory and Ergonomic Considerations	
	Benefits	Disadvantages
Biocular (one image source viewed by both eyes)	<ul style="list-style-type: none"> • Wider FOV, more information, easier to navigate • No interocular rivalry, as with monocular • Less complex to adjust than binocular • Simple electrical interface • Lighter weight than binocular • Less expensive than binocular 	<ul style="list-style-type: none"> • Heavier than monocular • Reduced luminance over monocular • No stereoscopic depth information • More complex alignment than monocular • Difficult to package, generally requires center of the forehead
Binocular (two image sources viewed by both eyes)	<ul style="list-style-type: none"> • Can provide stereo viewing • Better depth information for mobility • Improved target recognition over monocular • Partial binocular overlap • Symmetrical CM 	<ul style="list-style-type: none"> • Heaviest optics • Alignment and adjustments are more complex and critical than monocular • Most expensive

A binocular HMD is subject to the same stringent alignment, focus and adjustment requirements as the biocular design but with more packaging design freedom, because the designer is able to move both the optics and the image sources *away* from the face. This also means that the CM can be moved back towards the *tragion notch* to reduce biodynamic fatigue and improve safety (see Biodynamics section below). This is the most complex, most expensive and heaviest of all three optical design approaches, but one which has the advantage of providing the widest FOV possible and stereoscopic imagery from the two independent video channels. Examples are the Helmet Integrated Display Sighting System (HIDSS) (for the since-cancelled U.S. Army RAH-66 Comanche helicopter), the Joint Strike Fighter (JSF), Rotationally Symmetric Visor (RSV) HMD and the SR-100A HMD for simulation and training applications.¹² A binocular system can also take advantage of some techniques for extending the horizontal FOV without compromising resolution (see section below on Resolution Tradeoff with FOV).

Field-of-view

Field-of-view (FOV) describes how extensive the image appears to the user,¹³ measured in degrees as observed by one eye (for a monocular HMD) or both eyes (for either biocular or binocular HMDs).¹⁴ The human visual system has a total binocular FOV of 200° horizontal (H) by 130° vertical (V) (Smith and Atchison, 1997). While it is desirable to replicate this in an HMD, optical design and image source considerations limit our ability to do so.

¹² These systems are products of Rockwell Collins, Cedar Rapids, IA.

¹³ Field-of-view can be defined more formally as the maximum image angle of view that can be seen through an optical device.

¹⁴ It also may be measured as the diagonal FOV across the entire monocular or binocular field.

We must think about the FOV of an HMD differently than we do for a HUD,¹⁵ which is located in a fixed position in front of the pilot.¹⁶ Since HMD imagery moves with the pilot's head, and is always in a fixed location with respect to the head position, the displayed information is readily available anywhere the pilot is looking. This "unlocks" the pilot's view from the eye-to-HUD line-of-sight, contributing to the pilot's sense of self-stabilization, and lowering workload by reducing the amount and range of head movements necessary to capture the displayed symbology (Kasper et al., 1997; Szoboszlai et al., 1995; Wells, Venturino and Osgood, 1989).

Early helmet-mounted sights such as the Visual Target Acquisition System (VTAS – Belt, Kelley and Lewandowski, 1998; Dornheim, 1995) and the ODEN¹⁷ (Friberg, 1997; Waldelöf and Friberg, 1996) projected only a targeting reticle with a FOV of 6°. These, and the early Russian helmet-mounted sights, were elegantly simple, intended only for the task of aiming missiles away from the boresight of the aircraft, and they proved to be significant force multiplier for those pilots (Arbak, 1989; Merryman, 1994).

Early experiments with a more complete HUD-like symbol suite demonstrated that most fixed-wing pilots preferred the larger 20° FOV over a smaller 12° (Melzer and Larkin, 1987). Bahill, Adler and Stark (1975) found that most saccadic eye movements were in the $\pm 10^\circ$ to $\pm 15^\circ$ range. Any stimulus outside that range typically elicits a head movement to bring the object into a more "eyes forward" viewing position. If a designer decides to locate flight symbology such as altitude or pitch ladder along the outer vertical edges of the HMD the pilot should not be required to repeatedly rotate his eyes past the 10° or 15° point, as doing so will cause eye strain and probably reduce performance.

If our goal is to create an opaque, fully-immersive visual environment for gaming or simulation and training, a large FOV is desirable in order to stimulate the ambient visual mode¹⁸ and provide a more compelling sense of immersion. This is similar to the feeling encountered when watching a large screen IMAX[®] film, that of "being in" rather than "looking at" it. Patterson, Winterbottom and Pierce (2006) reviewed several perceptual studies on FOV. Allison, Howard and Zacher (1999 – cited in Patterson, et al., 2006) showed that limiting the FOV to 50° reduced the perception of self motion. Osgood and Wells (1991 – cited in Patterson, et al, 2006) showed that target acquisition in a simulated environment improved with increasing FOV, approaching a performance asymptote at 40°. Another study (Lin et al., 2002 – cited in Patterson, et al, 2006) showed increased levels of simulator sickness and "presence" up to 140° FOV. Based upon their findings, Patterson and his colleagues recommend a minimum 60°-FOV to achieve a full sense of immersion for simulator applications. One example of a wide FOV HMD is in the US Army's Aviation Combined Arms Tactics Trainer (AVCATT), a mobile, re-configurable training system for helicopter pilots that relies on the HMD for all the out-the-window visuals (Simons and Melzer, 2003) (see Chapter 3, *Introduction to Helmet-Mounted Displays*). This system uses a Rockwell Collins' HMD that provides a 100° (H) by 52° (V) FOV (recently upgraded to SXGA resolution). The price for this larger FOV is more head-supported weight. Although for these non-flight applications, it is tolerable over the training period and does not constitute a safety hazard to the user.

If the goal is a safety-of-flight-qualified HMD, then head-supported weight and CM become critically important, and a more moderate FOV of 40° horizontal by 30° vertical is acceptable. Reducing the FOV reduces head-supported weight/mass, which improves safety and reduces pilot fatigue, and the 40° horizontal FOV is within the threshold region of providing the "being in" rather than the "looking at" sensation. The IHADSS is an example of a 40° horizontal by 30° vertical FOV that has been successfully used on the US Army's AH-64 Apache helicopter since the early 1980's. The new RSV HMD for the Joint Strike Fighter also provides a 40° (H)

¹⁵ Typical HUD FOVs range from 10° to 18° for conventional non-pupil-forming designs, and up to 30° for the more complex, holographic, pupil-forming curved combiner designs.

¹⁶ Because the HUD does not move, designers must specify a relatively large "viewing eye box" within which the pilot can move his head and still see all the imagery. This drives the size of the combiners and the projection optics, which are competing for space on the very crowded forward cockpit panel.

¹⁷ ODEN is a 1990s HMS developed by FFV Aerotech, Sweden.

¹⁸ See Chapter 19, *The Potential for an Interactive HMD*, for an in-depth discussion of how an HMD stimulates the focal and ambient modes of vision.

by 30° (V) FOV to display symbology and real-time imagery. The AN/AVS-6 (Aviator's Night Vision Imaging System - ANVIS) NVG provides the helicopter pilot a fully overlapped 40° circular binocular FOV and also has been in use since the 1970s. For the dismounted Warfighter, the monocular AN/PVS-14 NVG also provides a 40° circular FOV. One notable exception is the QuadEye™ NVG currently in limited deployment for helicopter applications (see Chapter 3, *Introduction to Helmet-Mounted Displays*). While the ANVIS NVG has one image intensifier (I²) tube per eye, the QuadEye™ has two per eye and provides a panoramic 100° (H) by 40° (V) FOV (see Figure 3-25 in Chapter 3, *Introduction to Helmet-Mounted Displays*). The additional outboard I² tubes on each eye provide the pilot with more peripheral field imagery. The problem is the additional head-supported weight and more forward CM caused by the added I² tubes. Even though the design is based upon a lighter 16-millimeter (mm) tube versus the standard 18-mm tube, the mass is 700 grams versus 525 grams for the standard ANVIS NVG.

In most cases, it is necessary to match the FOV of the HMD with that of the sensor to achieve a 1:1 correspondence between sensor and display FOVs to ensure an optimum task configuration. Similarly, NVGs are specified to be a unity magnification. That is, the input FOV must match the output FOV to within a few percent.

Resolution

Resolution refers to the apparent angular size of a displayed pixel or image element and the ability for the user to view and correctly interpret an object as imaged by that pixel (and others). Resolution contributes to overall image quality, but there is also a direct relationship with performance. Increased resolution means there are more pixels or image elements available to let a Warfighter see the target. Depending on the user's task, the Johnson criteria (Lloyd, 1975) determines the resolution required to *detect* ("something is there"), *recognize* ("it's a tank"), or *identify* ("it's a T-72 tank") an object of a specific size at a given distance with an increasing number of pixels per target area required.¹⁹

Often the resolution of an HMD is given as the number of pixels on the image source for a given FOV value, and the user is left to determine the corresponding resolution. As sensor and image source technologies have improved, so has the user demand for better resolution, approaching the one-arc minute value associated with Snellen 20/20 human visual acuity.

If the user's task does not require identifying an object at great distance or the displayed imagery will only be HUD-like symbology, it may be preferable to reduce the resolution. It has been observed that an acceptable line width for HUD-like symbology should subtend on the order of 1 milliradian (3.4 arc minutes) as observed by the user. Anything smaller tends not to be visible (Boff and Lincoln, 1988).

But, even with a high quality flat panel image source, resolution is not simply a function of the number of pixels on a given target. As discussed in Chapter 4, *Visual Helmet-Mounted Displays*, the Modulation Transfer Function (MTF) is the measure of a display system's ability to transfer modulation from target to display as a function of spatial frequency. For a system such as the IHADSS, simply calculating the MTF of the HMD is not sufficient. This is because the HMD performance must be convolved with that of the imaging sensor and the transfer of video data to the HMD. Thus, while an HMD with very high resolution may provide a high quality image, visual performance of the user's overall visual system may still be limited by the resolution (and MTF) of the imaging sensor such as the forward-looking infrared (FLIR) or video camera (Velger, 1998). For NVGs, the resolution is a function of the performance of the objective lens, the I² tube and the eyepiece lens. For an aircraft

¹⁹ The Johnson Criteria says that for a 50% probability: 1) *Detection* requires 1.0 ± 0.25 cycles across the minimum dimension of the target, 2) *Recognition* requires 4.0 ± 0.8 cycles across the minimum dimension and, 3) *Identification* requires 6.4 ± 1.5 cycles across the minimum dimension. Increasing the probability to 90% requires an increase of 1.75X in the number of cycles across the minimum dimension (Leachtenauer, 2003). A new metric, Targeting Task Performance (TTP), that shows improvement over the Johnson Criteria has been recommended (Hixon, Jacobs and Vollmerhausen, 2004; Vollmerhausen, Jacobs and Driggers, 2003).

sensor system, such as the IHADSS, the resolution is a function of the performance of the sensor objective lens, sensor focal plane, image stabilization, image processing, video bus, HMD image source and the display optics.

Calculations of MTF for CRT-based displays are well known (Velger, 1998). MTFs of pixilated or “sampled data” displays such as Liquid Crystal Displays (LCDs) or Organic Light-Emitting Diodes (OLEDs) differ because of dependence on the phase of the input signal, as phase is shifted, there occurs a drop in modulation. Balram and Olsen (1996) and Olsen and Balram (1996) define the Multi-valued Modulation Transfer Function (MMTF), which includes the effects of frequency and phase and has a sync function-like appearance. More complex still is the effect of pixilated sensor data displayed by a pixilated image source, where changes in phase due to differences in residual distortion – barrel for the input sensor optics and pincushion for the HMD optics – can present a Moiré pattern.²⁰

Resolution tradeoff with FOV

Users typically want more of both FOV *and* resolution. This is not always possible because resolution often is a direct tradeoff with FOV, as a result of the “resolution/FOV invariant” (Melzer, 1998), and are related by the equation (Figure 17-2):

$$H = F * \tan \Theta \quad \text{Equation 17-1}$$

where F is the focal length of the collimating lens and:

- If H is the size of the image source, then Θ is the FOV, or the apparent size of the virtual image in space (which is desired to be large).
- If H is the pixel size, then Θ is the resolution or apparent size of the pixel in image space (which is desired to be small).

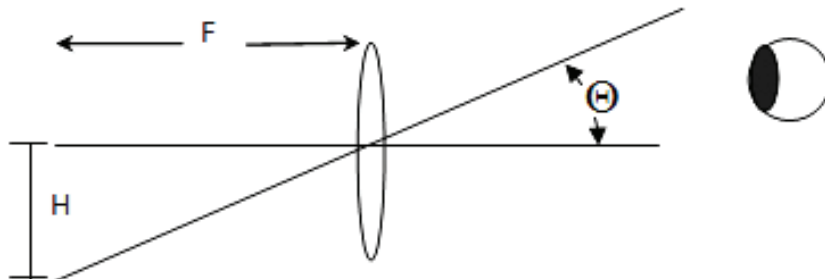


Figure 17-2. The relationship between the size of the image source and the resulting FOV or the size of the individual pixel and the resulting resolution.

Thus, the focal length of the collimating optics *simultaneously* governs the FOV *and* the resolution. For a display with a single image source, the result is either wide FOV *or* high resolution, but not both at the same time. Generally, a larger FOV is preferred in order to provide a more immersive experience. But, also, high resolution (small pixels) is desired: how high depends on the user’s task. If the task is nothing more than watching simple

²⁰ A Moiré pattern is an undesired image artifact; a geometrical design resulting from interference when one set of straight or curved lines is superposed onto another set.

video imagery, lower resolution may be acceptable. If the task is flying a helicopter at night, close to the ground, however, the best (highest) resolution possible is required to allow the pilot to see objects as small as power lines viewed at a distance or judge altitude using ground texture. If the human eye acuity of 20/20 it has a limiting resolution of 1 arc minute and this should be one resolution goal.

Given the $H = F \cdot \tan \Theta$ invariant, there are at least four ways to increase the FOV and still maintain resolution. These are: 1) partial binocular overlap, 2) optical tiling (which Moffitt, 2008, refers to as “paneled”), 3) high-resolution for a limited area of interest, and 4) dichoptic area of interest (which Moffitt, 2008 refers to as “mixed resolution”) (Hoppe and Melzer, 1999; Melzer, 1998). Of these, the first two will be discussed in detail, as they have been implemented in more than just a laboratory environment.

Partial binocular overlap results when the two HMD optical channels are canted either inward (*convergent* overlap) or outward (*divergent* overlap – see also Figure 3-3, Chapter 3, *Introduction to Helmet-Mounted Displays*). This latter configuration is similar to human vision with two monocular channels viewing the outward portion of the visual field and a central binocular region (Melzer and Moffitt, 1989; Melzer and Moffitt, 1991). Partial binocular overlap requires two image sources and two video channels with the optics and imagery properly configured to compensate for any residual optical aberrations.

Luning²¹ is a psychophysical binocular rivalry phenomenon observed in partial overlap displays from viewing dissimilar imagery with the two eyes. Concerns have been expressed about the minimum binocular overlap needed as well as the possibility that perceptual artifacts may have an adverse impact on pilot performance. Although the studies that found image fragmentation did place some additional workload on the pilot/test subjects (Klymenko et al., 1994; 2000), the research was conducted using static imagery. Although not substantiated by rigorous studies, anecdotal evidence indicates that users viewing dynamic imagery under some degree of workload – such as flying a helicopter simulator – do not experience the detrimental effects of luning. This agrees with earlier reports, which stated that users adapt to partial overlap after 30 minutes of use (McLean and Smith, 1987). Early efforts attempted to explain the difference in the *degree* of luning observed between convergent and divergent displays with an ecological vision model. Here, convergent overlap was theorized to induce less luning because it was more “ecologically valid” than the divergent case (Melzer and Moffitt, 1991). Several techniques have been shown to be effective in reducing the rivalry effects and their associated perceptual artifacts (Melzer and Moffitt, 1991; Moffitt and Melzer, 1993).

Good HMD design practice (similar to HUD design) dictates that the binocular alignment requirements for horizontal and vertical vergence be met within the central binocular overlap region (see Footnote 4 of this chapter), regardless of whether the HMD uses an extended configuration or not. The importance of ensuring good optical quality was shown in a series of experiments conducted using canted displays without sufficient optical compensation, resulting in subjects’ reports of eyestrain (Landau, 1990).

Another method of enlarging the FOV without compromising resolution is optical tiling. In this method, a series of small-FOV high-resolution displays are arranged in a mosaic pattern, similar to a video wall. Optically overlapping the display fields minimizes the seams between the adjacent tiles (Hoppe and Melzer, 1999). The overall FOV is the equivalent of all the tiles butted together, while the resolution remains that of the individual tiles or display modules. One example is the piSight™, developed by Sensics, Inc.²² The major difficulty with optical tiling is in positioning the image generator windows to provide good alignment and a smooth image across the tiles. Optical tiling also has been used with NVGs to enlarge the horizontal FOV (Jackson and Craig, 1999) – the QuadEye™.

A third method of enlarging the FOV involves providing mixed resolution (e.g., different resolutions for different FOVs and high-resolution insets) (Melzer, 1998; Moffitt, 2008). A low resolution, wide FOV channel is displayed to one of the user’s eyes while a much higher resolution, but smaller FOV channel is displayed to the

²¹ The term “luning” originated from the crescent-shaped edges of the circular image sources (e.g., CRT or fiber optic image bundle) (CAE Electronics, 1989).

²² Sensics, Inc., 810 Landmark Drive, Suite 128, Baltimore, MD 21061

user's other eye (Kooi, 1993). The user fuses the two images and suppresses the low-resolution central portion in favor of the higher resolution information, while retaining the wide FOV, low-resolution portion around it. The result is a high-resolution area of interest (AOI) that is fixed in the center of a wide FOV, but lower resolution, display.²³ This concept has been implemented on the Defense Advanced Research Projects Agency's (DARPA's) Multispectral Adaptive Networked Tactical Imaging System (MANTIS) prototype HMD to provide high resolution, wide FOV, multi-spectral imagery to the dismounted Warfighter. While creative in design, Curry, Harrington and Hopper (2006) have expressed concerns with this system on perceptual grounds, which have not yet been confirmed with laboratory or field testing.

Pupil-forming and non-pupil-forming optical designs

In an HMD, the optics serve to: 1) collimate the image source (creating a virtual image, which appears to be farther away than just a few inches from the face), 2) magnify the image source (making the imagery appear larger than the actual size of the image source), and 3) relay the image source (creating the virtual image away from the image source, away from the front of the face).

There are two optical design approaches common in HMDs. The first is the *non-pupil-forming* design or simple magnifier (Cakmakci and Rolland, 2006; Fischer, 1997; Task, 1997) (Figure 17-3). It is the easiest to design, the least expensive to fabricate, the lightest and the smallest, though it does have only a short throw distance between the image source and the virtual image, forcing the designer to locate the whole assembly on the front of the head, close to the eyes. It is typically used for simple viewing applications such as the Rockwell Collins' SO35A HMD for the Land Warrior program. (See Figures 3-30, 3-31, Mounted Warrior Soldier System HMD, and 3-32, Microvision, Inc's NOMAD in Chapter 3, *Introduction to helmet-Mounted Displays*.)

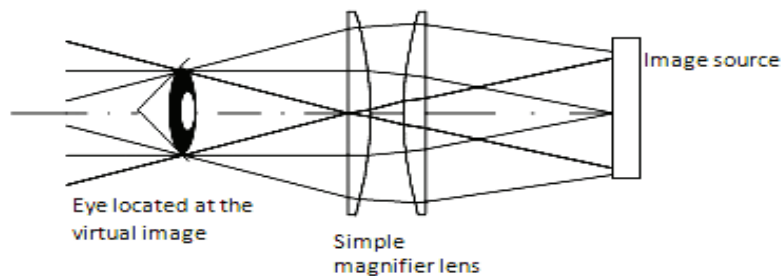


Figure 17-3. A diagram of a simple magnifier, a non-pupil-forming lens.

The second design form is the *pupil-forming* design (Figure 17-4). This is similar to the compound microscope, or a submarine periscope in which a first set of lenses creates an intermediate image of the image source. This intermediate image is *relayed* by another set of lenses to where it creates a pupil, or a hard image of the aperture stop.

²³ This dichoptic AOI approach is based on an eyeglass prescription technique used by optometrists known as *monovision*. A person whose eyes have limited ability to focus (a presbyope) is typically prescribed a bi- or trifocal correction. If this same person wants contact lenses, they are sometimes given a prescription in which one eye is corrected for near focus while the other is corrected for a distant focus. When the person attends to an object close by, the eye corrected for distance viewing is blurred. Similarly, when the person attends to an object at a distance, the eye corrected for viewing close up is blurred. The visual system suppresses the blurred image in favor of the non-blurred image (Schor, Landsman and Ericson, 1987). The dichoptic area of interest presents the wide field of view background image to one eye with the smaller image inset in the center. The user blurs that portion of the low-resolution image in favor of the higher resolution image.

The advantage is that the pupil-forming design provides more path length from the image plane to the eye. This gives the designer freedom to insert mirrors as required to fold the optical train away from the face and to a more advantageous head-supported weight and CM location. The disadvantages are that the additional lenses increase the weight and cost of the HMD and, outside the exit pupil, there is no imagery. The IHADSS and HIDSS HMDs are examples of pupil-forming HMDs (see Figure 3-22, Chapter 3, *Introduction to Helmet-Mounted Displays*).

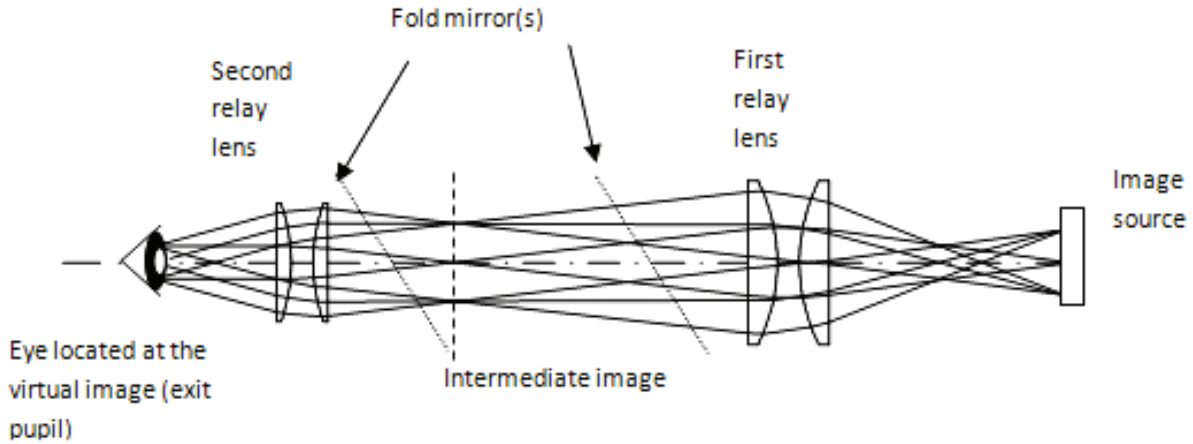


Figure 17-4. A pupil-forming optical design is similar to a compound microscope, binoculars or a periscope. Note that the increased length from image source to exit pupil provides the opportunity to insert mirrors to fold the optical path around the head.

Table 17-5 provides a summary of some of the advantages and disadvantages of pupil-forming and non-pupil-forming optical designs for HMDs.

Table 17-5.
Summary of some of the advantages and disadvantages of pupil-forming and non-pupil-forming optical designs for HMDs.

	Non-pupil-forming (simple magnifier)	Pupil-forming (relayed lens design)
Advantages	<ul style="list-style-type: none"> • Simplest optical design • Fewer lenses and lighter weight • Doesn't "wipe" imagery outside of eye box • Less eyebox fit problems • Mechanically the simplest and least expensive 	<ul style="list-style-type: none"> • Longer path length means more packaging freedom. Can move away from front of face. • More lenses provide better optical correction
Disadvantages	<ul style="list-style-type: none"> • Short path-length puts the entire display near the eyes/face • Short path-length means less packaging design freedom 	<ul style="list-style-type: none"> • More complicated optical design • More lenses mean heavier design • Loss of imagery outside of pupil • Needs precision fitting, more and finer adjustments

Exit pupil and eye relief

In all cases, the optical design must provide a sufficiently large exit pupil or viewing eye box.²⁴ This is the area shown in Figure 17-5 for the non-pupil-forming and Figure 17-6 for the pupil-forming system. A large exit pupil is important for a flight HMD, so the user doesn't lose the image if the HMD shifts on his head. A value of 12 to 15 mm has been deemed an acceptable value for these applications.

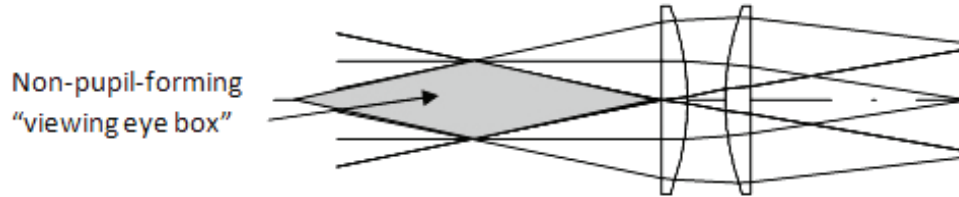


Figure 17-5. The viewing eyebox within which there will be unvignetted viewing of the HMD image source (shown in gray). Outside of that area, the image will vignette or be clipped, but still visible.

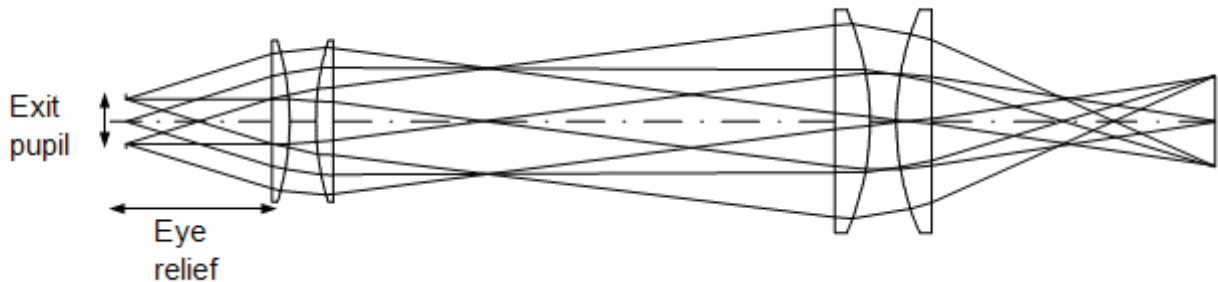


Figure 17-6. The exit pupil and eye relief of a pupil-forming optical design. Note that outside of the pupil area there is no imagery.

In Figure 17-7, it can be seen that the size of the off-axis exit pupil plays a disproportionately large role in determining the size and weight of the optics. The off-axis exit pupil is important for a partially overlapped HMD, where the on-axis ray from the image source actually traverses the off-axis portion of the optics. It is also important so the user does not lose the image when rotating their eyes to view imagery on the edge of the FOV, though most eye movements tend to be less than $\pm 10^\circ$ to $\pm 15^\circ$ (Bahill, Adler and Stark, 1975). Depending on the application, it is possible to trim the off-axis exit pupil so it is only 50% of the on-axis exit pupil diameter, reducing the size and weight, but not significantly reducing performance. By trimming the size of the off-axis exit pupil, we can reduce the size of the optics.

The HMD needs sufficient eye relief to allow the user to wear spectacles,²⁵ with a generally accepted minimum value of 25 mm. However, care must be taken with this terminology, because in classical optical design, the eye relief is measured as the distance along the optical axis from the last optical surface to the actual exit pupil. In most HMDs, the final optical surface in front of the eye may be an angled combiner which will fold the optical

²⁴ The exit pupil is found only in pupil-forming designs. In non-pupil-forming designs, it is more correct to refer to a *viewing eyebox*, because there is a finite unvignetted viewing area.

²⁵ Approximately one-third of U.S. Army aviators are required to wear vision correction, which increases as the population of qualified pilots ages. Though spectacles are the typical choice for visual correction, the U.S. Army has also investigated the use of contact lenses as well as surgical correction methods (Rash et al., 2002).

path to get the rest of the optics away from the front of the face, so the actual *eye clearance distance* (ECD) (measured from the face to the closest point of the combiner) may be considerably less. Thus, it is important that the useable distance from the eye to the first contact point of the HMD optics – the ECD – provide the minimum 25 mm.

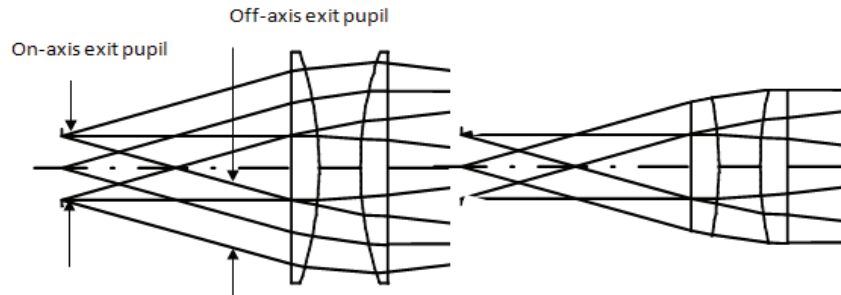


Figure 17-7. A comparison of the size of the collimating lens with full off-axis exit pupil (left) and the off axis exit pupil trimmed to 50% vignetting (right). Doing so significantly reduces the size and weight of the lens assembly.

Optical distortion

One of the important issues in an optical design is the control of residual optical aberrations such as focus, field curvature, and astigmatism. While this can be done with careful attention to the optical design, adding perhaps an additional lens or aspheric surface, distortion (defined as an off-axis image located at a different height than that expressed by paraxial equation) is more difficult to control, usually taking on a pincushion form in an imaging system. HMDs with off-axis optical designs (such as the JHMCS and JSF RSV) can have more complex asymmetric distortion. The result of residual distortion is:

- Non-linear motion across the FOV – an object moving across the visual field will appear to move at a different velocity at the edges of the field rather than in the center of the field.
- Non-linearity of horizontal and vertical lines – a horizon line that is supposed to be flat will be curved at the edges of the FOV.
- Binocular images don't line up – this is especially important in a partially overlapped binocular system where the edges of the field are in the center of the binocular field (Figure 17-8).

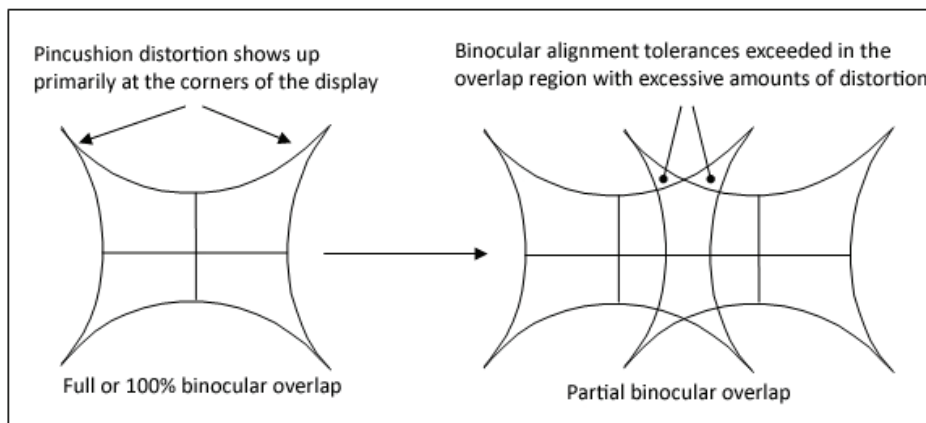


Figure 17-8. The effect of residual pincushion distortion on the binocular alignment in the overlap region. If the residual distortion is not properly controlled, it can induce eyestrain in the user.

If the HMD will be viewing imagery from a sensor, which generally has the distortion of the opposite sign, or “barrel,” it is possible that the pincushion distortion on the HMD may compensate, though not completely. In CRT-based HUD design, this can be corrected by pre-distorting the image plane. With a pixilated or finite-addressable display such as an LCD, however, the pixels cannot be moved, though it is still possible to *pre-distort* the imagery. Watson and Hodges (1995) reported a method of applying a geometric pre-distortion in the *texture* memory on high end image generators prior to final image rendering. Similarly, image warping engines are now available that accept imagery from a sensor, apply a polynomial correction to the imagery, and pass it on to the image source.

See through versus non-see-through HMDs

The decision to use a *see-through* or *non-see-through* HMD depends on the particular application, environment and the imagery desired for viewing. As with almost all HMD requirements, there are several key tradeoffs that must be made.

A see-through design is desired for aviation applications. Completely occluding one or both eyes is generally not acceptable. In particular, a see-through HMD design allows the superposition of imagery over the outside world, sometimes referred to as *augmented reality* (Azuma, 1997). As discussed in Chapter 19, *The Potential of an Interactive HMD*, see-through HMD imagery can be displayed in three frames of reference (Procter, 1999; Yeh, Wickens and Seagull, 1998): Aircraft-, earth- and screen-referenced.²⁶ With the HMD, navigational guidance and targeting data, as well as head-tracked sensor imagery, can be displayed. This allows a Warfighter to remain in contact with the real world and have the information aid in accomplishing the mission.

While the see-through design provides distinct advantages for an aviation application, it is a more difficult optical design because the see-through combiner must be large enough to provide sufficient FOV, exit pupil and eye relief without excess weight or adversely impacting pilot safety. Examples of see-through designs that use a separate optical combiner are shown in Figure 3-22 of Chapter 3, *Introduction to Helmet-Mounted Displays*; these include the IHADSS, HIDSS, Knighthelm, TopOwl[®], VCOP and Q-Sight HMDs. For many fighter aircraft applications, the protective visor also serves as the HMD combiner, such as in the DASH-3, JHMCS, and JSF RSV shown in Figure 3-20. In this case, it is necessary to stabilize the visor to ensure that it can still maintain the proper focus and binocular alignment tolerances.

Most aviation applications use only monochromatic imagery, typically centered at 555 nanometers (nm), because this is the peak daylight (photopic) visual sensitivity (Boff and Lincoln, 1988). One of the ways to improve both see-through transmission and reflectance is to take advantage of high reflectance holographic notch filters and V-coats.²⁷ The drawback is that while these special coatings reflect more of a specific display color, they transmit less of that *same* color, which makes the world look pink. With the advent of more use of color in the cockpit, selectively reflecting green over another color may miscue the pilot. For these reasons, many aircraft HMD combiners have spectrally neutral reflective coatings.

²⁶ *Aircraft-referenced* – An example would be in the RAH-66 Comanche helicopter program where a wire-grid frame was drawn to represent the front of the aircraft, giving the pilot an intuitive understanding of the direction of “aircraft-forward,” regardless of where his head was pointing. *Earth-referenced* – Here the pilot sees either real objects such as runways or horizon lines or virtual objects such as safe pathway in the sky, threat/friendly aircraft locations, engagement areas, waypoints, and adverse weather. Similarly, the pilot can be provided with head-tracked imagery as in the case of the AH-64 Apache helicopter or the JSF aircraft. *Screen-referenced* – This is information that does not require any reference to be seen, such as altitude, airspeed, or fuel status, similar to how a HUD displays this information. Also consider the case of a dismounted Warfighter viewing moving map information or text information. In this latter case, it may not even be necessary to have a see-through design. The first two require accurate head-tracking and image registration.

²⁷ V-coating refers to an antireflective boundary layer coating technique designed to reduce reflections at a single wavelength.

Spectral security is not generally as important in an aviation application because most aviation cockpit designs are governed by MIL-STD-3009, Department of Defense Standard for Lighting, Aircraft, Night Vision Imaging System (NVIS) Compatible (Department of Defense, 2001) which specifies different configurations for fixed- and rotary-wing applications.²⁸ The minus-blue filter on the NVGs filters out light below the 625 nm or 665 nm regions, primarily the red and orange spectrum. NVGs used by dismounted Warfighters, however, do not have this filter. Since the I^2 sensors are sensitive into the green spectral region, it means a dismounted Warfighter may give away his position at night if he is viewing imagery on a see-through HMD. In this case, a non-see-through HMD with an eyecup may be preferable. Without the need for a see-through combiner or the requirement for high luminance against a bright background, the end-to-end transmission efficiency is improved reducing the power for the image source.

Luminance and contrast

With the exception of flying with NVGs at night, every aviation task (both fixed- and rotary-wing) requires a see-through HMD to direct imagery to the user's eyes in much the same way that aircraft HUDs present imagery that is superimposed on the outside world. But the ability to see imagery in the high ambient luminance environment of an aircraft cockpit is counterbalanced by the need for high see-through transmission combiners on the HMD. To view the imagery against a bright background such as sun-lit clouds or snow, this less-than-perfect reflection efficiency means that the image source must be that much brighter. The challenge is to provide a combiner with good see-through transmission and still provide an image with sufficiently high contrast against the high luminance background. Figure 17-9 below, shows a diagram of a simple HMD optical design (see also Chapter 4, *Visual Helmet-Mounted Displays*). There are limitations, though, because most image sources have a luminance maximum governed by the physics of the device as well as by size, weight and power of any ancillary illumination. Other factors such as the transmission of the aircraft canopy and pilot's visor must be considered when determining the required image source luminance as shown.

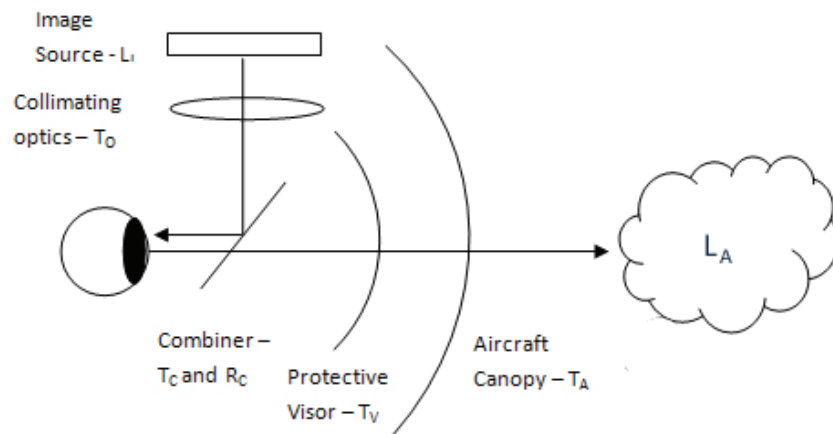


Figure 17-9. The contributions for determining image source luminance requirements for an HMD in an aircraft cockpit.

²⁸ MIL-STD-3009 (which replaced MIL-L-85762A) Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible, was written to guide aircraft cockpit designers (Breitmeyer and Reetz, 1985) in cockpit design that is compatible with night vision goggles by 1) limiting the spectral output of all interior display and cockpit lighting and 2) filtering the spectral response of the pilot's NVG so that when operational, no lighting would affect the gain of the NVGs. Helicopters with ANVIS goggles are Type I (direct view), Class A (625 nm minus blue filter). Fixed wing aircraft with a Cats-Eyes NVG are Type II (projected view), Class B (665 nm minus blue filter).

For the HMD design in Figure 17-9, the HMD luminance is given by:

$$L_{\text{HMD}} = L_I * T_O * R_C \quad \text{Equation 17-2}$$

where L_I is the image source luminance, T_O is the transmission of the collimating optics and R_C is the reflectance of the optical combiner. The pilot views the outside world through the combiner (transmission of T_C or $1 - R_C$ ²⁹), the protective visor (T_V , either Class 1 or Class 2³⁰), and the aircraft canopy transparency (T_A) against the background luminance (L_A). Thus, the background luminance observed by the pilot, L_O is given by:

$$L_O = L_A * T_A * T_V * T_C \quad \text{Equation 17-3}$$

For a see-through configuration, CR is given by the expression:

$$CR = \frac{(L_O + L_{\text{HMD}})}{L_O} \quad \text{Equation 17-4}$$

Combining Equations 17-2, 17-3 and 17-4, CR can be expressed as:

$$CR = 1 + \frac{(L_I * T_O * R_C)}{(T_C * T_V * T_A * L_A)} \quad \text{Equation 17-5}$$

For a nominal CR value of 1.2 against a worst case 10,000-foot-Lamberts (fL) background ambient (Foote, 1998), substituting values for the additional factors produces the required image source luminance values (L_I) presented in Table 17-6.

Table 17-6.
Required image source luminance is shown for four different HMD configurations.

		Case 1 Clear visor, 50% combiner transmission	Case 2 Dark visor, 50% combiner transmission	Case 3 Clear visor, 80% combiner transmission	Case 4 Dark visor, 80% combiner transmission
Collimating optics transmission	T_O	85%	85%	85%	85%
Combiner reflectance	R_C	50%	50%	20%	20%
Combiner transmission	T_C	50%	50%	80%	80%
Visor transmission	T_V	85%	15%	85%	15%
Aircraft canopy transmission	T_A	80%	80%	80%	80%
Ambient background luminance	L_A	10,000 fL	10,000 fL	10,000 fL	10,000 fL
Required image source luminance	L_I	1600 fL	282 fL	6400 fL	1129 fL

²⁹ To simplify our calculations, we will ignore Fresnel losses at each of the optical surfaces and assume that $T_C + R_C = 1$ although the small losses must be included in any rigorous analysis.

³⁰ Aviator visor configurations are given in MIL-V-43511. The Class 1 visor transmission is specified as $\geq 85\%$ and the Class 2 visor transmission is specified as between 12% and 18%. For our calculations the latter is assumed to be 15% transmission.

In the first two cases, we can see the impact of wearing a Class 1 (clear) versus a Class 2 (dark) visor on the required image source luminance. The dark visor reduces the ambient background luminance, improving HMD image contrast against the bright clouds or snow and reducing the required image source luminance. These first two cases are relatively simple because they assume a combiner with 50% transmission and 50% reflectance. Most pilots want higher see-through transmission because it allows them to see low-luminance targets at longer distances. This dictates a reduced combiner reflectance, demanding higher image source luminance. Cases 3 and 4 in Table 17-6 assume this higher transmission with both clear and dark visors, demonstrating how this requires higher image source luminance, which in-turn requires more power. While more power may not be an issue for the aircraft pilot, for the dismounted Warfighter – who carries his own batteries - HMDs power consumption is critical.

Helmet-mounted imaging sensors

The ANVIS and AN/PVS-14 NVGs have been implemented successfully to augment the Warfighter's vision in low light conditions. More recently long-wave thermal imaging has been added for dismounted Warfighters, under a program called Enhanced Night Vision Goggle (ENVG) and designated the AN/PSQ-20. These sensor systems typically mount to the front of the Warfighter's helmet, with the entrance aperture in line with the user's eye. While aiding the Warfighter in low light or night time conditions, these sensors have an adverse effect on head-supported weight and CM because the components protrude out in front of the user's face. A better approach would be to integrate the sensor hardware into the helmet so as to minimize bulk and protrusions and to better optimize weight and balance. Unfortunately, this can create an offset of the sensor aperture with respect to the wearer's normal line-of-sight.

Melzer and Moffitt (2007) investigated the perceptual and performance effects of viewing offset (forward, high and centered and side) monocular sensor video, replicating potential integrated design solutions for dismounted Warfighter applications. The results indicated little or no eye dominance issues but demonstrated that the sensor and display must be aligned to within 0.5° . If the alignment error was in the horizontal plane, subjects walked in an arc, rather than in a straight line.

Melzer and Moffitt (2007) also found that when aligned, the high-mounted sensor gave an indication of a slated floor, and the side mounted sensor produced a blind pointing error that was opposite of the sensor location. However, as long as the test subjects were able to view their feet and hands, they were able *re-calibrate* their hand-eye coordination to perform close-in tasks, albeit with some temporary after effects (Bertelson and de Gelder, 2004).

The offset sensors also may have implications in the cockpit, because in designing an aircraft cockpit, the starting point is the design-eye location³¹, the assumed origin from which the pilot will view out the windows and all cockpit displays. When helmet-mounted sensors are spaced further out than the assumed 2.5-inch nominal spacing, these assumptions may no longer be valid as the sensors may be staring directly into a canopy bow or strut. The result is that when looking at a see-through HMD, pilots may see one pair of struts with their normal vision and a second set of struts with their sensors.

The most common approach is to place night vision sensors on either side of the helmet, creating a perceptual condition referred to as hyperstereopsis. While this has been purposefully implemented to exaggerate stereo depth cues for enhancing detection of terrain drop off (Mohananchettiar et al., 2007), displacement of sensors in an aviator's HMD presents additional perceptual issues. The Thales TopOwl[®] has sensors located on either side of the helmet with a separation of approximately 10 inches (Priot et al., 2006).

Humans perceive depth visually several ways, based on both monocular cues (optical flow and optical expansion) and binocular (stereopsis). One of the key perceptual conflicts created in hyperstereopsis is the

³¹ In the design of human-machine interfaces (HMIs) (to include HMDs), the *design-eye position* is the position from which the user's eye is expected to view.

exaggeration of depth due to disparity magnification, which results in objects appearing closer than they are (object size is not affected, as there is no effect in the vertical direction). Helicopter pilots report feeling as though they have already landed, though they may still be a few feet off the ground. In addition, there are anecdotal reports of fixed-wing pilots “landing long” because they thought they were already on the ground. Kalich et al. (2007) describe the illusion as being in a “mountain top crater.”³² Flanagan, Stuart and Gibbs (2007a) found no effect on *absolute* distance perception, though they do state that this is unrelated to the impact of hyperstereopsis on *relative* distance perception. In another study, these same researchers (Flanagan, Stuart and Gibbs, 2007b) found that hyperstereopsis affected a pilot’s estimate of “time to contact”, making the approach seem faster than what would be expected with normal vision. In a third study, Stuart, Flanagan and Gibbs (2007), report that slope estimation is also affected. These researchers point out that although the effects were noted, the magnitude was not as much as would be expected from the 4X interocular separation. They speculate that even though the monocular and binocular cues are in conflict, the monocular cues are perceptually weighted more heavily than the incorrect binocular cues. They further speculate that because they found strong individual differences between subjects, it may indicate differences in the levels of suppression of these binocular cues and that this may be from individual adaptation strategies the subjects were using to overcome the perceptual errors. Given the reports of the pilots who have qualified with the TopOwl[®] (Mace, Van Zyl and Cross, 2001; Priot et al., 2006), it is tempting to speculate that subjects have the ability to adapt to the new perceptual condition. Bertelson and de Gelder (2004), use the term “re-calibrate” to describe such a condition where subjects adjust their hand-eye coordination to a new-found perceptual construct. Mohler et al. (2007) found that visual perception of the speed of self-movement will cause subjects to re-calibrate their visually directed tasks. There are, as yet, unanswered questions of how effective this re-calibration is and whether there are any residual aftereffects as pilots switch between the hyperstereo and normal vision.

Visual vs. Auditory Mode for HMDs

The visual channel is the mode of choice for providing information at high rates. However, for certain tasks and situations an auditory display may be more effective. Auditory displays are best used for alerting, warnings, and alarms situations in which the information occurs randomly and requires immediate attention. The near omnidirectional character of auditory displays is a major advantage over other types of HMD modes.

Table 17-7 (Deatherage, 1972, cited in National Research Council, 1997) summarizes some key factors when making a choice between an auditory and a visual display. Care must be taken that the auditory signal be consistent in its message or meaning (i.e., represent the same information in all situations) and not be too intense as to produce a startle response. Effective auditory displays should employ frequencies different from environmental background noise (to avoid masking); for choice situations, use moderate intensity, easily discernible frequency or amplitude signals; and use separate auditory warnings, different from other auditory signals (Hedge, 2007). Further discussion on the advantages of auditory cueing can be found in Chapter 14, *Auditory-Visual Interactions*, and Chapter 19, *The Potential of an Interactive HMD*.

Glumm et al. (1999) conducted a field study to investigate the effects of an auditory versus a visual presentation of position information on Warfighter performance of land navigation and target acquisition tasks. Additional measures of situational awareness, stress, cognitive performance, and workload were obtained. In the auditory mode, position information was presented in verbal messages. In the visual mode, the same information was provided in text and graphic form on a map of the area of operation presented on an HMD. During the study, 12 military volunteers navigated densely wooded unmarked paths that were 3 kilometers (1.9 miles) long.

³² “The observer describes the ground nearest to him as appearing closer (higher), with this exaggerated depth effect (the closer than effect) decreasing with distance away from the observer. When the helicopter is on the ground, the pilot perceives the near ground as being at chest level, while distant objects may look natural, a result of the non-linearity of the exaggerated depth perception with increasing distance from the observer.” (Kalich et al., 2007, page 3).

Although no differences were found between the two display modes in the frequency at which navigational and other tactical information was accessed, study participants reported that they maintained a greater awareness of position with respect to waypoints, targets, and other units when information was presented visually than when information was presented in an auditory mode via verbal messages. Although visual presentation of information appeared to enhance position awareness, differences between the two display modes in navigation and target acquisition performance were not found to be statistically significant. The findings of the investigation suggest differences in cognitive processing requirements between the two display modes and the impact of attentional focus and practice on cognitive performance.

Table 17-7.
Auditory vs. visual form of presentation.
(Deathridge, 1972; National Research Council, 1997)

Use auditory presentation if:	Use visual presentation if:
The message is simple (e.g., fire alarm).	The message is complex.
The message is short.	The message is long.
The message will not be referred to later (e.g., ambulance siren).	The message will be referred to later.
The message deals with events in time (e.g., telephone ring).	The message deals with location in space.
The message calls for immediate action (i.e., engine fire warning).	The message does not call for immediate action.
The visual system of the person is overburdened.	The auditory system of the person is overburdened.
The visual system is unavailable (e.g., receiving location is too bright or too dark; individual is asleep).	The receiving location is too noisy.
The person's tasks require him or her to move about continually.	The person's job allows him or her to remain in one position.
The origin of the signal itself is a sound (e.g., automobile horn).	

Acoustic/Auditory Guidelines and Recommendations

Human senses form a reception suite that provides orientation and security to human beings in a variety of conditions. *Vision* allows precise discerning of self-contained patterns and motion from a background covered by a FOV. *Smell* informs about a global invisible change in the environment that may affect human well-being and may crudely guide a person toward or away from the source. *Taste* confirms that what looks like a specific substance is really that substance and warns against the wrong kind of nutrient. *Touch* provides another type of feedback for our actions and often provides a last line of defense against immediate danger. *Balance* allows us to move and understand our relationship with the local environment. Finally, *audition* allows us to localize activities in a full 360° spherical angle that vastly extends our global FOV. While both the senses of smell and audition are comprised of telereceptors that inform humans about changes in global environment, only audition provides specific directional information needed to identify the location of a specific activity. Audition also allows hearing species to “see through visual obstacles” when some activity takes place within the FOV, but is invisible due to other objects obscuring its visibility or due to the opaqueness of the environment (e.g., nighttime, smoke, smog, mist, and fog). Auditory information can assist in guiding the more precise vision system toward the objects of interest and extends vision beyond the immediate foreground.

As all other senses, audition has its own strengths but also its own limits. The role of human factor engineers and interface designers is to maximize the use of all the senses in the multiple operational environments. The real

challenge is to enhance some sensory capabilities without reducing or making other the capabilities useless such that Warfighter safety or overall effectiveness is compromised.

The operational acoustic environment of the Warfighter is likely to be extremely varied. At one extreme, the surrounding environmental noise may be so intense as to preclude normal voice communication and reception of acoustic or audio signals. Such noise can be a serious source of stress as well as interference to both direct and radio communication. At the other extreme is the need for surreptitious activity in a quiet environment where any audible sound generated by the Warfighter or his equipment is to be avoided for security reasons. Either of these ambient conditions can restrict the utility of auditory communication and audio HMDs if they are not properly designed. Yet, in both situations audition may be the only remaining critical capability of the Warfighter. Many common military scenarios are very dependable on availability of auditory information, e.g., a Warfighter in hiding in direct visual proximity of the enemy forces, a combat engineer in a protective suit in chemically challenging environment disassembling an explosive trap, a squad entering a building, a fixed-wing aviator communicating during a 5G turn. Interviews with many Warfighters repeatedly confirmed that in limited visibility environment, they do not rely on the remaining visual information but react to what they hear. Unlike visual information, auditory information comes from all directions and over and “through” visual obstacles. Sound is often the first contact the Warfighter has with the enemy (Monroe, 2004).

As discussed in Chapter 5, *Audio Helmet-Mounted Displays*, the main audition-related challenge of Warfighters and underlying HMD-system developers and tacticians is to achieve an optimal balance between the Warfighter’s auditory awareness of the environment and uninterrupted, secure, low-level, and clear audio interconnectivity and to balance this against sufficient amount of hearing protection needed to for the ensure the Warfighter’s current and long-term hearing capability. Fortunately, there are some capabilities and technologies that can be combined to meet this challenge. As one example, bone conduction two-way interface permits relatively clear communication even in high level of surrounding noise. Bone conduction interfaces can be very inconspicuous, allowing them to be hidden from visual observation. They also are very sensitive to vocal tract changes and can transmit very low level acoustic signals as voiceless whisper, teeth clicking (e.g., Morse code), or other low level coded vocal signals. Recent research reports revealed that even changes in neural activity resulting in muscle changes during voiceless speech articulation can be used as audio input signal (Simonite, 2007; 2008).

Auditory awareness of the environment and hearing protection during sudden burst of noise, such as own and enemy fire power, explosions, sudden impact sounds, etc., can be optimized by the use of adaptive nonlinear hearing protection, as described in Chapter 5, *Audio Helmet-Mounted Displays*. These devices even may incorporate amplification of environmental sounds when needed for sound detection. However, fixed and permanent amplification of acoustic environment – either directional or not – has to be highly discouraged due to its detrimental effects of auditory distance estimation, general spatial orientation, and loss of hearing sensitivity to the sounds coming from the rear.

As technology and warfare becomes more sophisticated, Warfighter sensory and cognitive workload is steadily increasing, making proper utilization and specialization of sensory inputs critical. As for audition, its main function is to allow the Warfighter to understand the dynamically changing environment and to localize quickly – and this means detect early and localize relatively precisely – all the activities in the surrounding space, regardless of their direction. No other sense can substitute hearing in this capacity. Auditory localization precision degraded to 20 to 30° or an even larger angle can still be sufficient for navigation through a safe environment when the time of arrival is not a factor, but it could lead to increased casualties and a substantial drop in mission effectiveness and is especially detrimental to the operational conditions of the dismounted Warfighters. Sound signature recognition and identification are also important, but they can be supported by other senses, and thus being still important they are less critical in audio HMD design.

Meeting the challenges of the diverse and even sometimes contradictory requirements of an effective audio HMD demands good detectability and localizability of environmental events and should be regarded as the highest priority for audio HMD design. This is followed by effective speech communication and protection

against hazardous high level noise. Providing these capabilities requires a variety of acoustic and non-acoustic means to be considered and implemented whenever possible. A concise list of the main of these means includes:

- Exposure of both pinnae to environmental sounds or the use of a truly acoustically transparent headgear covering the ears (although recognized as difficult to achieve)
- An acoustically-optimized shape of the headgear (e.g., shell, headband) to minimize dispersion and shadowing of natural sounds
- Level-dependent in-the ear hearing protection to be used when hearing protection is needed
- No fixed and permanent environmental sound amplification; such devices, if incorporated, should be only turned on occasionally and should provide adjustable directivity enhancement
- Inconspicuous, always-on, audio communication system based on bone conduction or whisper-quality audio interface with an easy to access step-wise volume control
- Secure, fixed, but low pressure contact between the audio transducers and the user's head
- Speech-optimized audio transducers assessed for speech intelligibility using a variety of talkers and speech modes (see Chapter 11, *Auditory Perception and Cognitive Performance*)
- Provisions to use biological and chemical protection gear without detrimental effects on audio communication and noise protection
- Optional inconspicuous always-on environmental microphone to send continuous audio stream to commander or other receiving authority without Warfighter's intervention
- Optional tactile-based sniper detection and master warning interface (see Chapter 18, *Exploring the Tactile Modality for HMDs*)

Biodynamics Guidelines and Recommendations

The primary role of the Warfighter's helmet always has been to provide protection. This role has not changed and instead has been expanded with the introduction of HMDs to where the helmet is expected to serve as a mounting platform for the display without compromising the helmet's primary protective capability. These increasing demands means we must consider impact attenuation, head-supported weight, CM offset, frangibility, fit and comfort, retention and stability and their effects on head and neck biodynamics. Since these have not been addressed elsewhere in this volume, we will explore it in more detail in this section.

The human head weighs approximately 9 to 10 pounds (mass of 4 to 4.5 kg) and sits atop the spinal column. The occipital condyles at the base of the skull mate to the superior articular facets of C1, the first cervical vertebra (Perry and Buhrman, 1997; Melzer, 2006).³³ These two small, oblong mating surfaces on either side of the spinal column are the pivot points for the head. Their approximate location in the X-Z plane may be found by palpating the mastoid process (the pointed, bony structure behind the base of the ear). The CM of the head is located at or about the tragion notch, the small cartilaginous flap in front of the ear. Because this is *up* and *forward* of the head/vertebra pivot point, there is a tendency for the head to tip downwards, were it not for the strong counter force exerted by the neck extensor muscles – hence when individuals fall asleep, they “nod off.”

While the mass of a HMD system – and from this point forward, we are talking about the protective helmet and any head or helmet-worn protective gear, plus the display – is distributed over the surface of the wearer's head, a specific location can be defined where the HMD mass can be assumed to be concentrated, which we refer to as the HMD's CM and is expressed relative to a pre-defined coordinate system. For the U.S. Army, CM locations are defined with respect to the human head anatomical coordinate system (Figure 17-10) (Deavers and McEntire, 1993; Rash et al., 1996).

³³ There are seven cervical vertebrae. These are designated starting with C1 (the Atlas), C2 (the Axis), through C7, the bottom of which mates to the top of T1, the first thoracic vertebra.

The U.S. Navy and Air Force define CM locations relative to structural and anatomical reference points on the head of a crash test manikin (Albery and Kaleps, 1997; Thornton and Zaborowski, 1992). Adding mass to the head in the form of an HMD or NVGs can move the CM (now the helmet assembly + head) away from the ideal location. High vibration or buffeting, or dynamic events like ejection, parachute opening or crash can result in high accelerations of very short durations which will exacerbate the effect of this extra weight and displaced CM.

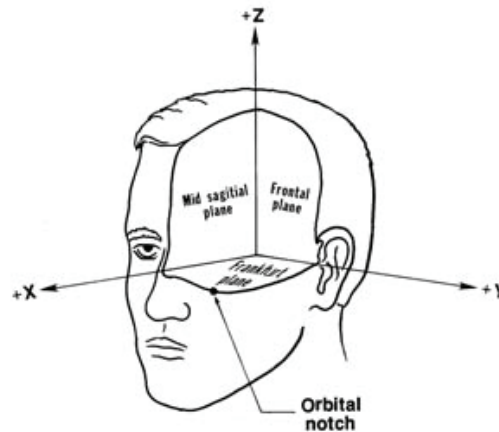


Figure 17-10 The anatomical coordinate system from which the head-supported weight/mass and center-of-mass (CM) requirements are calculated.

Key considerations of head-supported weight and CM must be consistent with levels of human tolerance so that during the course of a mission the wearer is not required to endure mission-compromising levels of head and neck fatigue or to require time afterwards to recover from induced neck pain. Effects can range from fatigue and neck strain to serious or mortal injury (Guill and Herd, 1989), as well as possible long-term cervical and spinal degradation.³⁴

An important difference between the aviator and the dismounted Warfighter is the measure of “success” after a dynamic event. A fixed-wing ejection or rotary-wing crash can be considered successful if the pilot can “walk away” even though he may not be considered combat effective immediately. On the other hand, the dismounted Warfighter who parachutes to the ground and is not immediately combat effective cannot be considered to have jumped successfully. This means we must consider different margins of safety between injury and non-injury depending on the Warfighter’s task.

Another concern is what effects specific operational factors (e.g., the Warfighter’s jump-induced stress or the pilot’s cumulative vibration or the pulling of Gs) in combination with the added stress of wearing an HMD may have on long-term degradation of the spine, e.g., causing chronic inflammation and pain. There has been investigation into the long-term effects of extended G-loading on spinal degradation for fixed-wing pilots (Burton,

³⁴ The human spine was not designed to support upright, bipedal posture. Rather, it was intended as a suspension bridge between the front and rear legs of quadrupeds. It has been shown there is an age-related loss in water content in the spinal disk, which nominally provides intervertebral cushioning. Cadaveric investigations have confirmed that degeneration starts in the late 20’s or early 30’s, and by age 40, almost all disks will have some form of degeneration - mostly asymptomatic - typically in C4/C5 and C6/C7, although primarily C5/C6 (Burton, 1999a, Burton, 1999b, Burton, 1999c). This degeneration is exacerbated under acceleration, shock and added g-forces (Harms-Ringdahl et al., 1999). Under constant loading, there appears to be long-term mechanical creep of the intra-spinal disk material resulting in reduced intervertebral spacing. Frequent insult can result in osteophytic growth, which further restricts mobility, resulting in an often painful constriction of the nerve root exiting the neuroforamen. This has been found in fighter pilots, rugby players, gymnasts, wrestlers and with automotive injuries (Burton, 1999b). Interestingly, studies of individuals who carry upwards of 200 lb on their heads many times per day show little degeneration, most likely because they maintain an upright, neutral position during the process, minimizing insults to the facet joints and intervertebral disks.

1999a; Burton, 1999b; Hämäläinen and Kuronen, 1999; Harms-Ringdahl, Linder et al., 1999) and some for rotary-wing pilots (Butler and Alem, 1997), though nothing has been done to specifically address the long-term effects of repeated parachute opening shock, parachute landing fall or of long-term helmet wear on dismounted Warfighters. However, given the evidence of long-term effects on pilots and other non-aviation activities, it is difficult *not* to speculate a causal relationship between a Warfighter's activities and some level of long-term degeneration.

Because the environments are different for rotary-wing (long duration missions, high vibration levels), fixed-wing (shorter duration missions, but higher G-loading) and ground combat, fatigue-minimizing design measures, though similar, differ in their specific values. Historically, head-supported weight and CM requirements have been nonexistent or vague. These requirements often were written loosely and based on existing designs. Language in helmet development specifications often resembled statements as "...the helmet CM must be located as close to the head CM as possible," "...lighter and CM no worse than current helmet systems," "provide ease of head movement," and "...(have) reduced bulkiness." These requirements provided little detailed guidance to the design teams and could not be quantitatively evaluated.

During the 1990s, the U.S. military attempted to better define head-supported weight and CM requirements for head-borne devices. In 1991, the U.S. Air Force published interim head-supported weight and CM criteria for its fixed-wing helmets (the "Knox Box" and the "Tolland Box" see Perry and Buhrman, 1997; Knox et al., 1991; MacMillan, Brown and Wiley, 1995; Settecerri, McKenzie, Privitzer and Beecher, 1986); these criteria were developed to keep neck compression loads at an acceptable level during ejection.

In 1998, the USAARL published a set of two curves that defined limits of acceptable longitudinal and vertical CM location as a function of head-supported weight, commonly referred to as the "USAARL curves" (see Figure 17-11, Ashrafiuon, Alem and McEntire, 1997; Barazanji and Alem, 2000; Harding, et al., 1998; McEntire, 1998c; McEntire and Shanahan, 1998). These were developed to provide HMD designers with guidance that would minimize performance degradation during typical helicopter flight scenarios (Alem and Meyer, 1995; Butler, 1992), as well as minimize the risk of acute neck injury during severe, but survivable, helicopter mishaps (McEntire and Shanahan, 1998). Since their publication, the USAARL curves have become the de facto standard for the design of rotary-wing aviation helmet-HMD systems.

Studies conducted by all three U.S. military services since the USAARL curves were published have investigated the effects of head-supported weight and CM location on the risk of neck injury during dynamic events (Bass et al., 2006; Brodin et al., 2008; Doczy, Mosher and Burhman, 2004; Halldin et al., 2005; Merkle, Kleinberger and Uy, 2005). Additionally, several of these studies have shown crash severity and head-supported weight to have the greatest influence on the risk of neck injury (Brodin et al., 2008; Halldin et al., 2005; Paskoff, 2004).

The USAARL and the U.S. Air Force Research Laboratory (AFRL) also have conducted studies investigating the effects of variables such as head-supported weight, CM position, and gender on wearer fatigue and performance (Barazanji and Alem, 2000; Eveland et al., 2008; Eveland and Goodyear, 2001; Fraser et al., 2006). Barazanji and Alem (2000) determined that the biomechanical response of female subjects wearing varying head-supported weight while subjected to simulated helicopter environments was similar to that of males (Butler, 1992) and recommended there should be no gender-specific head-supported weight and CM criteria. Fraser, Alem and Chancey (2006) found that increased head-supported weight and anterior CM position had significant adverse effects on Warfighter performance in visual tracking tasks. Conversely, AFRL research has shown that head-supported weight and CM location did not have a significant effect on performance in tracking tasks during exposure to sustained acceleration (e.g., as experienced during air combat maneuvering) (Eveland and Goodyear, 2001).

Biomechanics research at the U.S. Air Force's Wright-Patterson Laboratories has established head-supported mass and CM boundaries for fixed-wing HMDs, essentially a refinement of the "Knox Box."³⁵ Using the occipital

³⁵ Plotting the CM spatial limits on an X-Z plane yields a rectangle commonly known as the *Knox Box* (Knox et al., 1991).

condyles (the pivot of the head about the C1 cervical vertebra – located approximately between the two points of the mastoid process just behind the ears) as the origin point, these are:

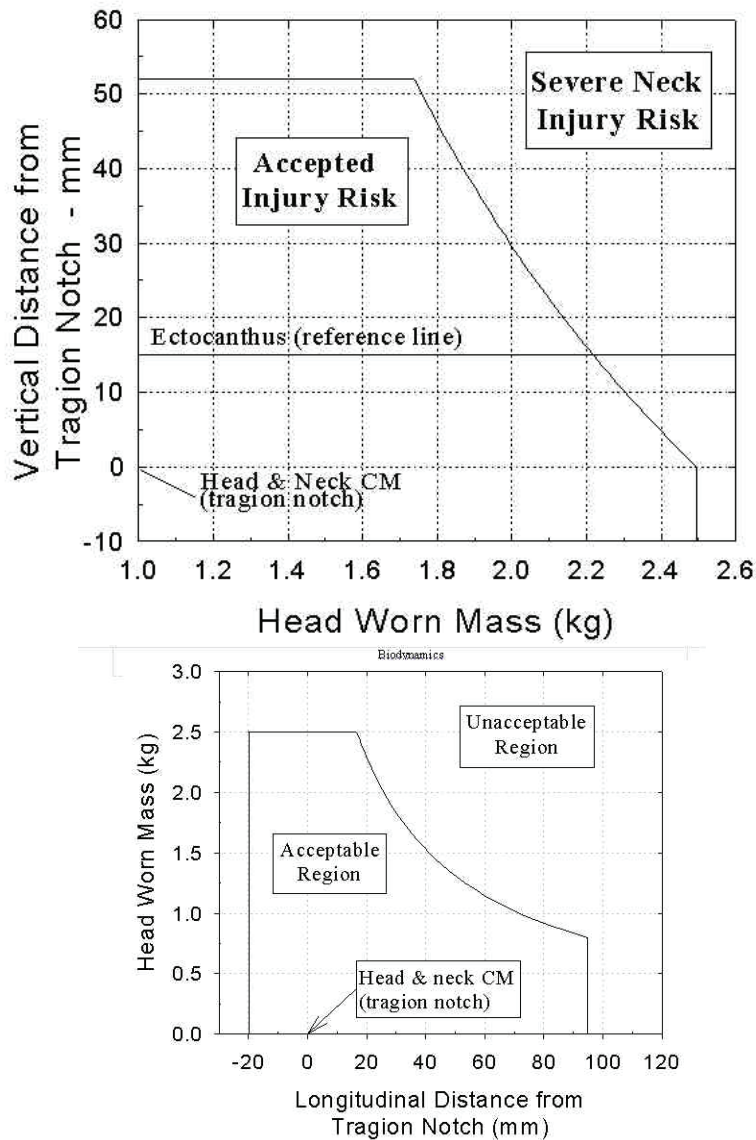


Figure 17-11. Vertical CM location as a function of head-supported weight/mass (top); allowable head-supported weight/mass as a function of longitudinal CM location (bottom).

- Maximum head-supported weight of 5 lb (2.5 kg) (including MBU-20/P oxygen mask and 3 inches [7.6 cm] of hose, helmet, visor and HMD components).
- Vertical CM limits (z-direction): Between +0.5 inches (1.3 cm) and +1.5 inches (3.8 cm) above the occipital condyles.
- *Threshold* CM horizontal limits (x-direction): between +0.5 inches (1.3 cm) forward and -0.8 inches (2 cm) aft of the occipital condyles.

- *Objective* CM horizontal limits (x-direction): between +0.2 inches (0.5 cm) forward and -0.8 inches (2 cm) aft of the occipital condyles.
- Lateral CM limits (y-direction): ± 0.15 inches (± 0.4 cm).

For the purposes of repeatable measurements and proper fitting, the test uses the size large Adam manikin head. This eliminates the impact of variations in human anthropometry (Buhrman, 2009).

Recommendations for dismounted Warfighters are unfortunately less well-defined. Researchers have examined injuries during dismounted Warfighter parachute operations (Bar-Dayana, Bar-Dayana and Shemer, 1998; Craig and Lee, 2000; Craig and Morgan, 1997; Ekeland, 1997; Lowdon and Wetherill, 1989). In most cases, it was concluded that most parachute jump injuries occurred on landing. The most compelling research to date on the effects of head-supported weight and CM on neck strain for dismounted Warfighter parachute jumps was performed at the USAARL (McEntire, Alem and Brozoski, 2004; McEntire and Alem, 2002; McEntire, Brozoski and Alem, 2003) in response to the additional head-supported weight required for the US Army's Land Warrior HMD program. They concluded that "inertial loads created during parachute opening shock with existing helmets do not frequently exceed human tolerance."

McEntire, Brozoski and Alem (2003) further compared their results to the Federal Motor Vehicle Safety Standards (FMVSS) values for neck injury and found that peak force and moment values were well below the accepted limits. The authors further compared their results with newly-proposed neck injury curves for flexion and extension ($+M_y$ and $-M_y$, forward and rearward bending around the ear-to-ear, or Y axis, respectively) using the Abbreviated Injury Scale (AIS)³⁶ severity scale of "3" (serious). They found a probability of injury to be less than 0.1%. This seems to agree with the findings of Craig and Morgan (1997), which found a 0.15% rate for back and neck injuries.

McEntire, Brozoski and Alem (2003) make it clear that although cadaveric and instrumented manikin results are useful, the data should be viewed carefully because of the lack of voluntary muscle control exerted during the events. Since the subjects cannot respond, there is also the lack of data regarding the "Ouch" factor, or the resulting instantaneous, post-event or chronic pain (McEntire, 2005, private communication). To address the remaining knowledge gaps, the USAARL is embarking on a three-year research effort into the development of models of cervical spine degeneration. One objective of this research program is to develop head-supported weight and CM location guidelines for mounted and dismounted Warfighters.

Frangibility

Frangibility refers to the ability of an HMD component to break free from the overall helmet-HMD system during a dynamic event. The purpose is to "shed" mass from the HMD system, thereby reducing the risk of neck injury during a dynamic event such as a helicopter mishap or ejection. Frangibility often is desired and even required when the total head-supported weight and CM creates the potential for unacceptable risk of neck injury.

A classic example of frangibility dates to the U.S. Army's early version of NVGs (AN/PNS-5). The AN/PVS-5 NVG was attached to the Soldier's Protective Helmet-4 (SPH-4) aviator helmet with "hook and pile" fasteners and elastic tubing. This did not allow the NVGs to easily or consistently detach during a crash. During ANVIS development, the attachment mechanism was re-designed with a spring-loaded "ball and socket" engagement, allowing the NVG to separate from the mount when exposed to a 10G to 15G load. The IHADSS helmet-display unit (HDU), mounted on the right lower edge of the helmet shell, is also designed to detach from the helmet under crash loadings. Shannon and Mason (1997) concluded a 10-year retrospective database study to determine the

³⁶ The *Abbreviated Injury Scale* (AIS) is an anatomical scoring system first introduced in 1969 to provide a reasonably accurate ranking of the severity of injury. Injuries are ranked on a scale of 1 to 6, with 1 being minor, 5 severe and 6 an unsurvivable injury.

injury rates of U.S. Army aviators involved in accidents and the relationship to wearing NVGs. Crewmembers wearing the non-frangible AN/PVS-5 NVG were shown to have 162% greater likelihood than non-NVG users to experience head or neck injury. Conversely, crewmembers wearing the frangible ANVIS had only a slightly higher, but *non-significant*, risk of head and neck injury as compared to non-NVG users. This reduced-injury probability was attributed to the frangibility of the ANVIS.

Current U.S. Army aviation frangibility (breakaway) design requirements state that when subjected to an acceleration of 9G or less in any vector within the limits described in Figure 17-12, the designed frangible components will *not* separate. However, separation *must* occur for acceleration of 15G or greater; and during breakaway, the frangible components should not come in contact with the wearer's forehead, eye sockets, or facial regions (Rash et al., 1996).

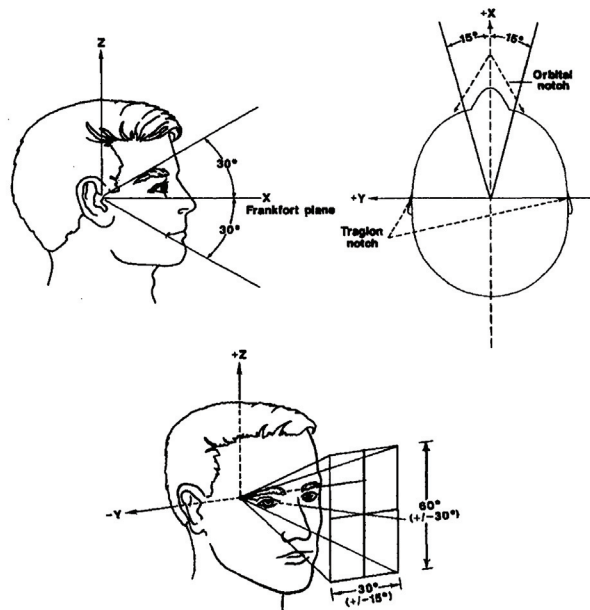


Figure 17-12. Vector limits for HMD breakaway force. If a 9G force occurs anywhere within the shown limits, the components will break away.

Frangibility also may be desirable for HMDs used in ground combat operations. Warfighters exiting military vehicles, moving through vegetation, or performing operations in urban environments are at risk of inadvertently snagging HMD cables (McEntire, 1998b). If the cable snags, tension in the HMD cable could induce excessive neck loading. A cable safety disconnect would reduce the risk of neck injury resulting from these mishaps.

Impact attenuation

Head impact injury is the leading cause of permanent disability and fatality in Army aviation rotary-wing mishaps (Shanahan and Shanahan, 1989; Shannon, Albano and Licina, 1996) and has been a major concern for aviators (Paschal et al., 1990; Trumble, McEntire and Crowley, 2005). This requirement is met with an outer shell and sufficient distance (volume) between the shell and the skull filled with energy-absorbing material (such as expanded polystyrene foam, see Brozoski and McEntire, 2003). The protective shell also resists penetration from sharp or jagged impact surfaces and distributes the load over a greater contact area.

Human tolerance to blunt head impacts is an area of ongoing research. Over the past 40 years, the USAARL has analyzed crash-damaged helmets and has recommended blunt impact performance standards for U.S. Army aviation helmets (McEntire, 1998a; Reading et al., 1984; Slobodnik, 1980). For the current generation of U.S.

Army aviation helmets,³⁷ the USAARL has recommended test head form accelerations thresholds of 150G to 175G, depending on the impact location. The USAARL-recommended value for the headband region (175G) is based on the concussion threshold to linear accelerations, not on skull fracture, fatality, or rotational acceleration thresholds. The recommended value for the earcup and crown regions (150G) is based on the risk of basilar skull fracture concomitant with impacts to those areas and the high frequency of occurrence in Army helicopter crashes (Shanahan, 1983). Impact attenuation requirements for military aircrew helmets continue to become more stringent.³⁸ Table 17-8 compares the impact and penetration resistance requirements for the HGU-56/P (rotary-wing) and the HGU-55/P (fixed-wing) helmets.

Table 17-8.

Differences for impact and penetration resistance values for the HGU-55/P (for fixed-wing applications) and the HGU-56/P (for rotary-wing applications).

Helmet	Impact Resistance	Penetration Resistance
HGU-56/P	Crown - <150g @ 4.8 m/sec Headband - <175 g @ 6.0 m/sec Earcups - <150g @ 6 m/sec	5 kg impactor, dropped from 1.52 m Max tear length <5 cm
HGU-55/P	<150g for less than 6 ms <200g for less than 3 ms <400g maximum	<0.25 inch penetration with 16 oz weight dropped from 10 feet

Fit, comfort and stability

It is difficult to put a precise metric on the fit or comfort of an HMD, though it is always immediately evident to the wearer. Even if the HMD image quality is excellent, the user will reject it if it doesn't fit well. Fitting and sizing is especially critical in the case of a HMD where in addition to being comfortable, it must provide a *precision* fit for the display to remain stable relative to the pilot's eye(s). Important issues for achieving a good fit with an HMD include:

- The user must be able to adjust the display to see the imagery.
- The HMD and helmet must be comfortable for a long duration of wear (4 to 6 hours) without causing "hot spots" and resist heat buildup.
- The HMD and helmet must not slip with sweating or under G-loading, vibration, or buffeting.
- The HMD and helmet must be retained during crash or ejection (except where breakaway capability is required).
- The weight of the head-borne equipment must be minimized.
- The mass-moment-of-inertia must be minimized.
- The mass of the head-borne components should be distributed to keep the CM (center-of-gravity) close to that of the head alone.

With the emphasis now being placed on blunt impact protection for ground Warfighters, combat helmet fitting systems are required to also provide blunt impact protection (Department of the Army, 2007). This is a paradigm

³⁷ The current standard US Army aviator's helmet is the HGU-56/P Aircrew Integrated Helmet System (AIHS), which is worn by all helicopter pilots with the exception (as of this writing) of the AH-64 Apache pilots.

³⁸ The Modular Aircrew Common Helmet (MACH) is a tri-service program intended to produce one common fixed- and rotary-wing helmet for the Army, Navy, and Air Force, to reduce the number of helmet configurations in the Department of Defense (DoD) inventory, reduce the logistical footprint, provide an effective platform for helmet mounted devices and increase aircrew safety.

shift from the aviation environment where the fitting system is not designed to contribute to the impact energy attenuation capabilities of the helmet. In addition to comfort, stability, and impact attenuation, additional attributes of fitting ease, sanitation, adjustability, durability, and maintainability should be considered when selecting a fitting system.

Another parameter is the anthropometric range³⁹ for the subject population and the number of helmet sizes needed. Fewer helmet sizes suggest the fitting system accommodate a greater anthropometric range. If designing a helmet system with a restricted exit pupil location, numerous helmet sizes may be required with a minimal thickness fitting system. One of the most common mistakes made by designers is to assume a correlation between various anthropometric measurements, because almost all sizing data are *univariate* – that is, they are completely uncorrelated with other data. For example, a person who has a 95th percentile head circumference will not necessarily have a 95th percentile interpupillary distance (Whitstone and Robinette, 1997). This was shown in a bivariate study that attempted to correlate head length and head breadth for male and female aviators, showing a large spread of data (Barnaba, 1997). Table 17-9 presents Gordon’s et al. (1989) univariate (uncorrelated) anthropometric data for key head features for the range of sizes of the 5th percentile female up to the 95th percentile male.

Table 17-9.
The univariate (uncorrelated) anthropometric data for key head features.
Range of sizes for the 5th percentile female up to the 95th percentile male.
(Gordon et al., 1989) (expressed in cm)

Critical head dimensions (cm)	5% female	95% female	5% male	95% male
Interpupillary distance (IPD)	5.66	6.85	5.88	7.10
Head length	17.63	19.75	18.53	20.85
Head width	13.66	15.25	14.31	16.08
Head circumference	52.25	57.05	54.27	59.35
Head height (ectocanthus to top of head)	10.21	12.09	10.89	12.77

Note: The *head length* and *head height* measurements are head-orientation dependent.

Numerous methods of achieving a custom helmet fit have been devised. These include foam pads, sling suspension systems, and mesh-and-drawstring systems like that used with the AH-64 Apache helicopter specific IHADSS (Rash, 2001), as well as fitting systems that line the entire interior contour of the helmet such as the Thermoplastic Liner™ and the ZetaII™ (Figure 17-13). While differing in concept, these fitting systems each act as a physical interface between the wearer’s head and the interior contour of the helmet’s energy-absorbing liner (Rash, 2001).

Emerging HMD systems such as the TopOwl® and the Advanced Distributed Aperture System (ADAS™) simplify the fitting systems by creating custom energy-absorbing liners (EALs) for individual wearers, using data from three-dimensional laser scanners to create a model of the wearer’s head. The data are used by a computer-controlled milling machine to carve the EAL from a block of expanded polystyrene foam (Brozoski and McEntire, 2003). The result is an EAL with a customized interior contour that matches contour of the intended wearer’s head. Helmet manufacturers must still determine the minimum allowable EAL thickness needed to meet the impact attenuation requirements of the helmet. Knowing this, helmet designers work from the inside out to determine the number and size of helmet shells needed to accommodate the anthropometric range of the user population.

³⁹ *Anthropometry* – “the measure of Man” – is the compilation of data that define such things as the range of height for males and females, the size of our heads and how far apart our eyes are. Used judiciously, these data can help the HMD designer achieve a proper fit, though an over-reliance can be equally problematical.



Figure 17-13. Thermoplastic Liner™ (left) and Zetall™ (right) helmet fitting systems.

Helmet retention

Helmet retention refers to the ability of the helmet to stay in place on the wearer's head during dynamic events such as helicopter mishaps, ground vehicle accidents, or high speed ejections. This is critical because the helmet cannot perform its protective function if it has departed the wearer's head or it has rotated to a position that leaves the skull open to direct impact.

The helmet retention system and, to a lesser extent, the fitting system are responsible for keeping the helmet in place during dynamic events. The *fitting system* provides frictional resistance to helmet motion relative to the head. The *retention system* performs the primary role of keeping the helmet in place by "anchoring" the helmet to prominent anatomical regions on the head. Reading et al. (1984) showed that the helmet retention system failure was a significant factor in mishaps where helmet losses occurred. Typically, modern retention systems consist of an integrated nape strap and a chinstrap. The nape strap runs behind the head just under the occipital region. The chinstrap runs under the chin, being careful to avoid the areas around and about the trachea. Properly designed, a retention system will prevent excessive forward or rearward rotation of the helmet when the head is exposed to dynamic accelerations (Hines et al., 1990).

Helmet retention requirements have typically consisted of a chinstrap load test. In these tests, the helmets were fixed in place while the chinstrap was loaded to a predetermined level. These tests checked the structural integrity of the retention system stitching and fastening systems, as failures of these components were identified as causes of retention system failure and helmet loss (Reading et al., 1984; Vyrnwy-Jones, Lanoue and Pritts, 1988). While chinstrap strength and elongation play a part in helmet retention, these quasi-static tests do not replicate the inertial loading experienced by the helmet-HMD system during aviation or ground vehicle mishaps. For this reason, dynamic retention tests like those developed by the USAARL (Brozoski and Licina, 2006) also are being incorporated into modern helmet performance specifications (Department of Defense, 2007).

Biodynamic and protection recommendations

- Because inertial loading has been shown to play a significant role in the risk of acute neck injury, head-supported weight and CM for the helmet and HMD combination must be tightly controlled relative to established standards for the Warfighter's specific environment.

- Where appropriate, inertial neck loads resulting from adverse head-supported weight can be reduced through the use of frangible devices. Properly designed, these have been shown to reduce the risk of neck injury.
- Blunt impact protection should be a primary consideration from the outset of any HMD design. If an HMD is to be designed for use with an existing helmet, modifications that will degrade the impact attenuation properties of the helmet – especially those that reduce the stopping distance between the outer shell and the skull – must be avoided.
- The range of head sizes for the targeted user population and the role the fitting system will play in the HMD system must be well defined. The expected anthropometric range of wearers and minimum thickness of the fitting system will dictate the number of helmet sizes needed to fit the expected users. An over-emphasis on anthropometric data and an under-emphasis on fitting have resulted in extra helmet sizes and user rejection for comfort (Whitestone and Robinette, 1997).
- Retention system materials must be of sufficient strength to withstand the expected inertial loads without failure. The angular displacement of the helmet-HMD system relative to the head, resulting from the dynamic pulse, should not result in any optical systems, supporting surfaces or frames contacting the face, eyes, or forehead regions.

Perceptual and Cognitive Recommendations

HMD design is multidisciplinary involving both technology and the human perceptual system as discussed at length throughout this volume (see also Chapter 19, *The Potential of an Interactive HMD* for more information on cognitive processes and HMD interaction). Technology will change over time – more pixels in the displays, faster processors, lighter weight materials, smaller packaging and lower power consumption – but the human user will not. Rather, research will continue to uncover more about how humans interact with technology – a relatively new field called neuroergonomics (Parasuraman, 2003) – and provide us with better insight into how to design the human interface to the technology.

The HMD offers an opportunity to provide information to the Warfighter that uniquely replicates the way humans explore the environment by moving their head and eyes. This allows the Warfighter to remove the restrictions of the limited visual field of the cockpit, ground vehicle or hand-held display while enabling the ability to create situation awareness (SA) through the repeated information gathering, updating and prediction cycles necessary to accomplish his mission. Since the HMD must not compromise safety and it shares the valuable space on the head with a protective helmet, display components must earn their way onto the head by contributing to SA without incurring size, weight, power and cognitive overload penalties.

Too often HMDs provide only a re-mapping of head-down display information, placing the burden on the user to quickly process the raw *metaknowledge* with a minimum expenditure of cognitive resources. This is not always the case. The HMD can enable the user's *filter* (by directing his attention to key events) and *fuel* (energizing his perceptual and cognitive resources) aspects of attention by the use of a head orientation tracker to quickly and accurately register the line-of-sight. If Earth-referenced (or conformal) or vehicle-referenced imagery is displayed on a see-through HMD, time-critical data can be cognitively obtained without placing additional workload on the user. One example is the Advanced Non-Distributed Flight Reference symbology (Jenkins, 2003; Jenkins, Turling & Brown, 2003; Jenkins, Sheesley and Bivetto, 2004, and see Figure 19-3) that quickly and intuitively informs the pilot of flight attitude and orientation. This provides the ability to maintain SA cycle without having to move the head back to the narrow FOV of the HUD or without the workload penalty from with switching attention (Spence and Driver, 1997). There also has been considerable research on the efficacy of using cross-modal cueing such as auditory as an alert for an impending time-critical visual event. It has also been found that 3-D audio cueing can enhance SA by superimposing geospatial directionality on cues or communications (Bolia, 2004).

User Adjustment Recommendations

One last but very important topic is that of the most direct interface the user has with the HMD, i.e., the controls that provide the user the ability to make adjustments to the display's characteristics. Despite the trend and the various arguments for automatic or self-adapting circuits and systems, the unique environments and situations encountered by the Warfighter, coupled with the potentially severe outcomes, argue for providing the user with the capability to make control inputs for the purpose of optimizing HMD information. Until advances in a number of scientific fields allow what would currently be considered as "futuristic" user-directed inactive control over HMD functions, (see Chapter 19, *The Potential of an Interactive HMD*), such adjustments most likely will be accomplished by hands-on controls, although voice-activation methods are an alternate approach (Baron and Green, 2006; Cohen and Oviatt, 1995; Kamm, 1995).

On HMD devices, both monocular and binocular, there should be mechanical, electronic, and/or optical adjustment mechanisms available for the user to optimize the attributes of the imagery and selection of displayed information. The mechanical adjustments are used primarily to align the optical axes and exit pupils of the device to the entrance pupils and primary lines of sight of the user, if required by the inherent design. The electronic adjustments may include display brightness, contrast, electronic focus, sizing, sensor sensitivity characteristics (gain and off-set for thermal sensors), etc. The optical adjustments may include the focus adjustments for the eyepieces and sensor objective lens, and magnification selection for targeting and pilotage sensors.

Recommendation Summary

Throughout this chapter, we have presented the various options HMD designs emphasizing the need to understand the user, their required tasks and environment – a human-centered design focus. In so doing, we identify the key requirements that are absolutely necessary – a process known as sub-optimization:

- *Ocularity* – If the Warfighter needs to only briefly view imagery such as maps or text, then a simple monocular HMD is sufficient (e.g., SO35A for Land Warrior). It will also be the lightest, least complicated and the least expensive. For longer term viewing, a monocular HMD may be acceptable (i.e., IHADSS or JHMCS), but a binocular design is best (i.e., HIDSS or JSF RSV), especially for fully immersive simulation and training applications (e.g., SR100A). This latter configuration provides best viewing comfort and improved detection, though it may be heavier, more complex and more expensive.
- *Field-of-view* – A large FOV (i.e., $>60^\circ$) provides a sense of "being in" an image, key for immersive training and simulation applications. While also desired for flight applications, this must be balanced with biodynamics considerations that limit the horizontal FOV to approximately 40° (e.g., IHADSS and ANVIS NVGs). This must also be weighed against resolution requirements because the larger the FOV, the lower the resolution. Partial binocular overlap and optical tiling can enlarge the FOV without compromising resolution, but these do have their limitations.
- *Resolution* – While the limit of human visual resolution is 1 minute of arc, few HMDs can provide this primarily due to limitations in sensor and image source technologies. For an aircraft system (e.g., AH-64 Apache), it is not sufficient to specify just the HMD image source pixel count. Rather, we must compute the contributions from all subsystems from sensor to eye.
- *Pupil-forming versus non-pupil-forming optical design* – A non-pupil-forming design is best for a simple HMD viewing application. It will also be the most compact, the lightest, the least expensive and the imagery is viewable outside the "viewing eye box." The pupil-forming design is heavier and more expensive because of the additional lenses, though the longer path length provides design freedom to package the HMD around the head or protective helmet, moving the CM towards a more compatible location.

- *Exit pupil and eye relief* – These metrics represent the ability to comfortably view imagery, especially in an operational environment. The larger the exit pupil, the more tolerant the HMD will be to movement on the head during use. With a pupil-forming design, the image is not viewable outside the design exit pupil, so a minimum of 12 mm to 15 mm should be required, though the (operationally successful) IHADSS HMD has only a 10-mm exit pupil. With a non-pupil-forming design, the image is viewable even when outside the eye box, so the exit pupil may be smaller. The off-axis exit pupil (for both design forms) has a disproportionately large impact on overall optic size and weight, so allowing it to vignette (up to 50%) by truncating the diameter of the lens will reduce weight. A longer eye relief improves viewing comfort and allows users to wear prescription eyewear with the HMD, however, since most combiners are tilted, the classically defined eye relief (along the optical axis) is not always an accurate measure. Rather, we should consider the ECD, the distance from the eye to the closest point of the tilted combiner, which should be a minimum of 25 mm.
- *Optical distortion* – Residual optical aberrations can adversely affect image quality and these can be addressed through thorough evaluation of image quality during the design process. Residual distortion is not as easily managed as it may require additional lenses for correction. In this case, it is possible to pre-distort the image prior to the image source.
- *See-through versus non-see-through considerations* – If the HMD is intended for fixed- or rotary-wing applications, a see-through HMD is needed. This lets us superimpose symbology or imagery (aircraft- versus earth- versus screen-referenced) on a see-through combiner. Doing so unlocks the pilot from the limited and fixed-forward FOV of the HUD or cockpit displays, providing imagery wherever he is looking. Pilots would like to have a combiner with as much see-through as possible to let them see farther, though this has implications for the image source luminance. For a Warfighter viewing text or map information, a non-see-through design may be preferable because: 1) this type of imagery could be confusing against a normal background, 2) the non-see-through design has better image source to eye transmission and will therefore require less power and 3) a non-see-through design will be more covert at night.
- *Luminance and contrast* – In order for the Warfighter to see the HMD imagery, we must know the range of ambient light levels in which he will prosecute his mission. For a pilot to view HMD imagery against a high ambient background, we must determine the transmission values of the canopy, any visor and the combiner to arrive at a value for the image source luminance based upon a minimum contrast ratio requirement. For the dismounted Warfighter wearing a non-see-through display, a value of 35 fL to 50 fL should suffice for daytime viewing with the ability to reduce the luminance to 0.1 fL at night.
- *Considerations for helmet-mounted sensors* – Adding sensors to a Warfighter's helmet (e.g., the AN/PVS-14 or AN/PSQ-20) augments their vision under low light conditions, but when configured in line with their eyes may have negative head-supported weight and CM/CG effects. Mounting the sensors at a more favorable location on the top or sides of the helmet may present adverse perceptual artifacts such as offset hand-eye coordination (monocular) or hyperstereopsis (binocular). Limited data indicate that a perceptual re-calibration is possible, though with unknown residual aftereffects. Research is continuing in this area.
- *Acoustics/Auditory* – The helmet/head-gear component of the HMD system should optimally allow for exposure of both pinnae to environmental sounds or for the use of an acoustically transparent headgear covering the ears. This headgear should have an acoustically-optimized shape to minimize dispersion and shadowing of natural sounds. Level-dependent, in-the ear hearing protection is recommended when hearing protection is required. An always-on audio communication system based on bone conduction or whisper-quality audio interface with an easy to access step-wise volume control should be employed. Designs should include provisions to use biological and chemical protection gear without introducing detrimental effects on audio communication and noise protection.

- *Biodynamics* – The primary purpose of the Warfighter’s helmet is protection and only secondly as a mounting platform for the HMD components, which – because of the additional head-supported weight and CM – can contribute to increased fatigue and injury potential. Strict guidelines for head-supported weight and CM have been established which will minimize this likelihood for pilots. For the dismounted Warfighter, these guidelines have not been as firmly established. Though most head and neck injuries occur upon parachute landing fall, strict limits are still being determined. In all cases, the implications of long-term wear of a helmet with HMD components have not been established, though research is also continuing in this area.
- *Perceptual/Cognitive* – All HMD components should earn their way onto the head because they reduce Warfighter workload and enable him to accomplish his mission. Information should not simply be a re-mapping of available cockpit information, but should be cognitively pre-digested to ease the transfer of information while not overloading working memory.
- *User adjustment* – The selection and implementation of available adjustments must allow for individual differences while carefully avoiding complexity and minimizing the potential for misadjustment.

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