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Head Mounted Display Guidelines for Future Vertical Lift Aircraft

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Introduction

In rotary-wing aircraft, the purpose of a helmet mounted display (HMD) is multi-faceted. First and foremost, it provides pilot situational awareness with symbology, representing various flight parameters and positional information. An HMD can integrate symbology with pilotage imagery from aircraft sensors as well as from onboard terrain databases or other *a priori* databases including synthetic imagery of man-made structures and other objects. Three-dimensional symbology can conform to the terrain and mark a landing site that provides visual cueing for safe landing under brownout conditions. For attack helicopters, the HMD and integrated helmet system serves as the central display system for entire weapons systems, providing line-of-sight weapons cueing, targeting information from onboard sensors as well as from remote unmanned aircraft systems (UAS), and head tracking for slewed weapons systems. Distributed aperture systems, like the prototypes developed under the Army's Operational Pilotage for Utility and Lift (OPUL) program or the Special Operations Advanced Distributed Aperture System (ADAS) program, allow for the stitching of imagery from multiple aircraft sensors based on pilot head position, providing for increased situational awareness with a possible 360-degree field-of-regard (FOR).

The integration of avionic displays and weapons systems is best served when the resolution of the display system matches or exceeds the output of aircraft sensor systems. The Integrated Helmet and Display Sighting System's (IHADSS) helmet display unit (HDU), in the AH-64 Apache, was composed of a miniature cathode ray tube (CRT) with relay optics and a combiner lens. The HDU's 30-degree vertical field-of-view (FOV) was composed of 875 CRT raster lines that extended over a 40-degree horizontal FOV (Harding et al., 1995; Rash et al., 1996). Initially, the display exceeded the output resolution of the AH-64's Primary Night Vision System (PNVS) and Target Acquisition Display System (TADS). For approximately the first three decades of the AH-64's operational deployment, the AH-64 was thus sensor limited. The AH-64 sensor suite has undergone significant improvements over the last decade. The AH-64E's Modernized Target Acquisition Designation Sight/Pilot Night Vision Sensor (M-TADS/PNVS) with much higher native resolution and a horizontal FOV that exceeds 50 degrees, is now display limited (at least in terms of its HDU). Given the 1970's technology driven HDU's limited resolution and FOV, valuable sensor information is being lost or truncated for a pilot's "heads-up, eyes-out" experience (Colucci, 2018). This display limitation occurred because the HDU remained essentially the same even though improvements were made to the Apache helmet with its migration to a variant of the Head Gear Unit-56-Personal (HGU-56P) helmet with head tracking and HDU mount.

Lessons can be learned from the Apache's evolution to the modern-day AH-64E aircraft. In the 1970s, the Honeywell, Inc.-designed (now Elbit Systems, Inc.) HDU was ahead of its time in terms of sensor requirements. Four decades later, the HDU is still operational, albeit it is now the weakest link in the proverbial chain from target sensing to pilot vision. In light of the Apache's life cycle development efforts, over-designing the HDU seems appropriate. Case in point, the HMD in the Air Force's F35 is estimated to cost $400,000 (Colucci, 2018), but each eye's FOV only matches that of the 40-year-old IHADSS. The binocular display has 100% overlap of each eye's FOV (each eye shares the same FOV). The F35 pilot views 30 by 40-degree sensor imagery that is stitched together from its distributed aperture system, allowing the pilot to view the outside world even through aircraft structures. One must surely ask, however, is a 30 by 40-degree FOV adequate? Or the corollary, is the Air Force likely to redesign the F35 helmet to increase the FOV of the HDU anytime soon? The answer to the second question is surely not likely. The question about the adequacy of a 30 by 40-degree FOV is much more difficult to answer.

The consequences of reduced FOV can be observed in pilot behavior. In night operations, experienced pilots using an Aviator Night Vision Imaging System (ANVIS) typically increase head movement to scan the outside world. The ANVIS' circular 40-degree FOV is much like viewing the world through a cardboard toilet paper roll. The ANVIS FOV represents only about 5% of a normal eye's visual field area. The 40-degree circular field, however, has proved more than adequate as it has allowed Army aviation to "own the night." However, even night vision goggles have seen improvements to provide increased FOV. For example, panoramic goggles with twin tubes optically coupled over each eye more than doubled the horizontal FOV. The center tubes provide full overlap with each eye's outside tube providing a monocular FOV extension.

There are significant differences between the HMD requirements for rotary-wing versus fast jets. Pilotage and situational awareness are important to rotary-wing aviation as is weapons delivery for attack helicopters. For fighter jets, weapons delivery is key. The U.S. Army Aeromedical Research Laboratory (USAARL) has always maintained that the minimum FOV required for rotary-wing pilotage is 40 degrees. For weapons sighting or symbology, smaller FOV are adequate. As an example, for the Army's Common Helmet Mounted Display (CHMD; McLean et al., 2016a, 2016b), designed for utility and lift helicopters to provide flight symbology and landing assistance during brownout, a smaller FOV is adequate. The answer to the adequacy of a 40-degree FOV for pilotage was likely the result of a past compromise between the need for larger FOV and the need for increased resolution (Melzer, 1988; Melzer et al., 2009). For a fixed display format, increases in FOV resulted in decreases in resolution and vice versa. The rapid improvements in commercial display technologies with their concomitant increases in resolutions to 4K and beyond, should provide HMD manufacturers a technological basis for producing HMDs with larger FOV, while also increasing spatial resolution to match or exceed the spatial resolution of aircraft sensors.

Figure 1. RAH-66 Comanche HIDSS prototype consisting of two monocles with overlapping FOV.

In this paper, we are suggesting and will provide additional justification that the Army should not settle for a horizontal FOV any smaller than 52 degrees. Why 52 degrees? The Army should capitalize on past achievements and 52 degrees was the binocular FOV specification for the Comanche Helmet Integrated Display Sighting System (HIDSS) that was under development during the 1990s and prototype systems achieved this specification (Harding et al., 1998). The HIDSS was composed of two monocle displays that closely mimicked IHADSS HDU specification (Figure 1). The FOV of each eye was partially overlapped, creating area coverage composed of binocular and monocular FOV; see Klymenko et al. (2001) for performance issues associated with partially overlapped binocular FOV. Figure 2 shows the FOV measured in an early version of the HIDSS (from Harding et al., 1998). We are not suggesting that partial overlapping FOV is the only way to achieve 52 degrees. On the contrary, today's higher resolution display formats are likely sufficient to have fully overlapping 52-degree FOV.

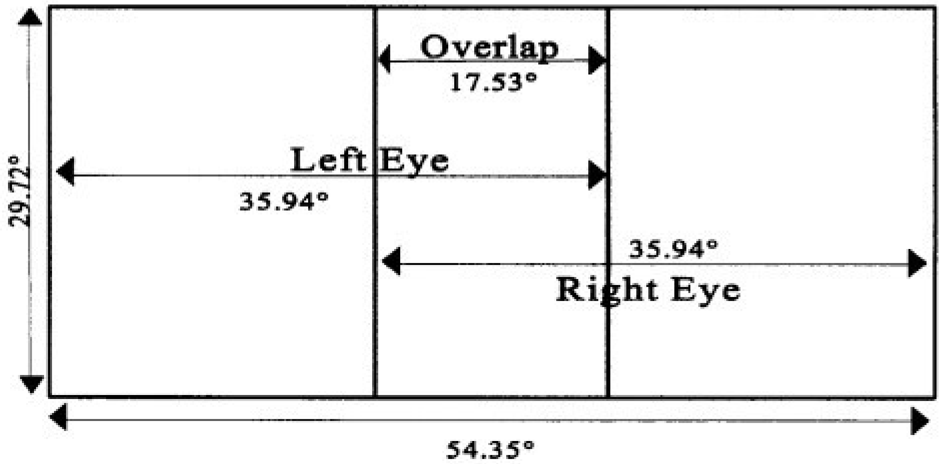

Figure 2. Measured binocular FOV in early version of RAH-66 Comanche HIDSS (from Harding et al., 1998).

There are also other differences between rotary-wing versus fixed wing aircraft, which makes for more rigid rotary-wing HMD specifications. For example, crash protection is paramount in rotary-wing helmets with additional head supported mass and center of gravity requirements (i.e., "USAARL Curves;" McEntire & Shanahan, 1998). Also, vibration in rotary-wing aviation is much more severe than in fixed-wing aircraft and helmets must be designed to reduce slippage. For example, without proper helmet fitting for Apache pilots, IHADSS imagery was often reduced in contrast or even lost entirely due to the HDU's 10 millimeter (mm) exit pupil slipping below the entrance pupil of the eye (Rash et al., 1987).

In this report, suggested guidelines will be provided that describe aspects of HMD performance that meet the Heads-Up, Eyes-Out primary display requirements of FVL platforms. These guidelines are designed to (1) be technologically achievable; (2) meet the vision needs of Army aviators; and (3) meet day/night/degraded visual environment (DVE) operational requirements. Additionally, the FVL HMD should match or exceed the display requirements of onboard and off-board sensors; and must be compatible with other systems and protective equipment.

Discussion

Anticipated Sensor Display Requirements and Display Resolution

Harding et al. (2020) discussed likely sensor requirements for the Future Long Range Assault Aircraft (FLRAA), the Army's planned replacement for the UH-60 Black Hawk. The sensor suite includes a terrain following/terrain avoidance radar system capable of penetrating likely DVE obscurants, visible and infrared (IR) camera systems with optical zoom for threat identification and targeting, long wave infrared (LWIR) sensor with selective filtering for improved visibility during brownout and dust storms, night imaging I^2 and thermal sensors for pilotage and threat detection, and a multi-wavelength light detection and ranging (LIDAR) to achieve three-dimensional view of forward terrain and obstacles. It was recommended that sensor imagery be augmented with *a priori* terrain databases with improvements and other features marked and coded and with synthetic imagery showing conformal landing symbology along with recent improvements.

The exact sensor particulars that will be mounted on FVL platforms (particularly FLRAA and the Future Attack and Reconnaissance Aircraft [FARA]) are not known at this time, however we can make certain assumptions about their FOV and resolution. As a starting point, the AH64E Apache's Modernized Target Acquisition and Designation Sight/Primary Night Vision Systems (M-TADS/PNVS) displays an image with a Nyquist frequency (sampling rate divided by two) of about 16 cycles/degree which is about the same as the IHADSS HDU, albeit the sensor has a FOV that is about 12 degrees wider horizontally than the HDU. However, contrast in the CRT based IHADSS is much lower (approximately 0.1; Figure 3). The excitation profile in the HMD's P43 phosphor essentially limits contrast much beyond the Nyquist frequency. Compare this to pixelated displays whose modulation transfer function (MTF) is represented by a sinc function (Infante, 1993):

$$\mathrm{MTF}\ (m) = ½\sin\ (p\ F_f^{0.5}\ X_p\ m)\ /\ (p\ F_f^{0.5}\ X_p\ m)½ \tag{1}$$

where µ is spatial frequency, F_f is fill factor (active display pixel area ÷ total pixel area), and X_p is pixel pitch (pixel spacing) in mm. As presented in the left graphic in Figure 3, at the Nyquist frequency of a pixelated display (e.g., flat panel display), contrast exceeds 0.6 even for a fill factor of 1.0 (active pixel area covers entire pixel space). Lower fill factors result in even greater contrast.

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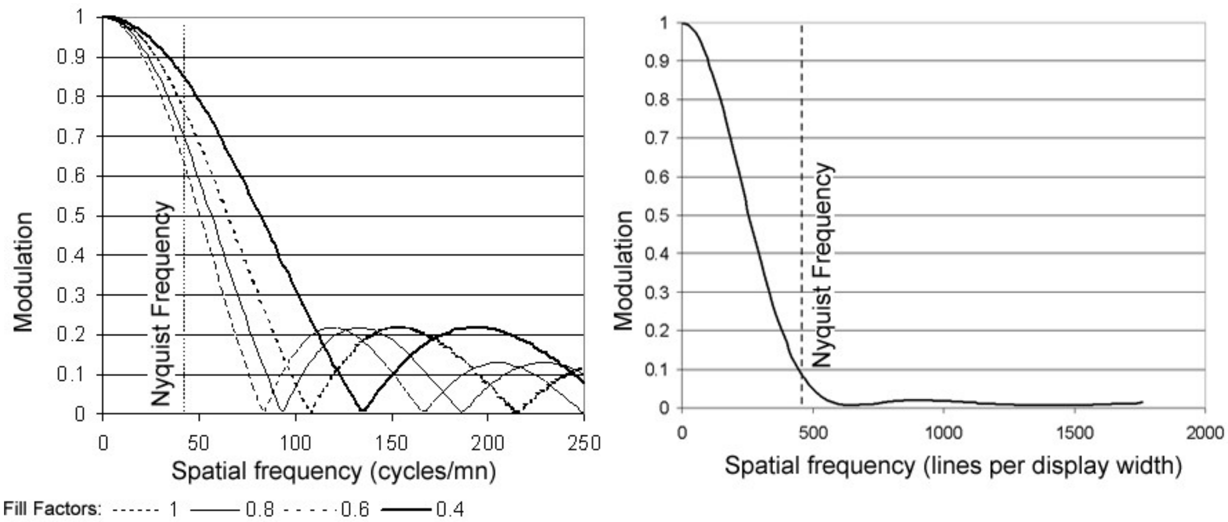

Figure 3. Modulation transfer functions for a 12µm flat panel display with four different fill factors (left figure) and the MTF of the IHADSS HMD (right figure). The Nyquist frequency is represented by the vertical line in each figure. From Figures 1 and 2 of Harding & Rash (2004).

Because of the image smear in CRT displays, it is highly likely that not only are there FOV limitations with the IHADSS HMD, there are also contrast limitations where sensor contrast is greatly reduced. Essentially the same resolution used in the Apache IHADSS and the Apache M-TADS/PNVS, was also specified for the RAH-66 Comanche HIDSS. Table 1 shows the range of FOVs achievable for various display formats using the same Nyquist figure.

The half cycle width for a 16 cycles/degree resolution is just fractionally higher than the gap or stroke distance used in Snellen 20/40 letters (2 arcminutes). In terms of human contrast sensitivity (i.e., 1 ÷ threshold contrast), young adults with good vision (e.g., majority of Army aviators) can generally detect high luminance/high contrast sinusoidal grating patterns with a frequency approaching 60 cycles/degree (Figure 4). Aviators' contrast sensitivity at 16 cycles/degree is above 100 representing a contrast threshold of less than 0.01 (< 1.0%).

Table 1. Achievable FOV, With a Nyquist Frequency of 32 Cycles/degree, As A Function of Display Format

	Number of Displayed Pixels		**Full Overlap FOV (degrees) at 32 pixels/degree**	
Nomenclature	**Horizontal**	**Vertical**	**Horizontal**	**Vertical**
5K	5120	2880	160	90
4K	3840	2160	120	67.5
QHD (WQHD, 1440p)	2560	1440	80	45
WUXGA	1920	1200	60	37.5
Full HD (FHD); 1080p	1920	1080	60	33.75
HD; 720p	1280	720	40	22.5
XGA	1024	768	32	24

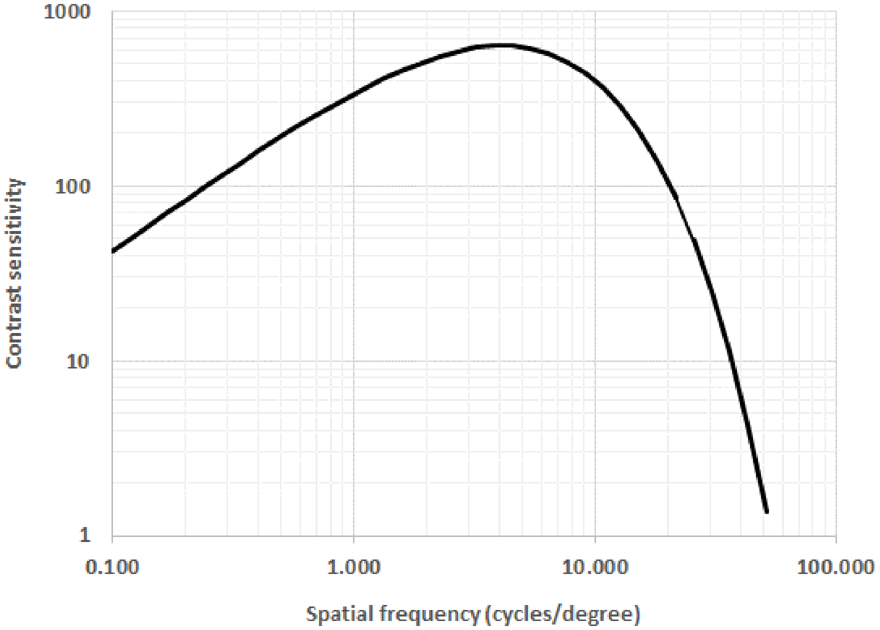

Figure 4. Modeled contrast sensitivity of a young adult with good vision for sine wave gratings of 100 fL average luminance. Calculated from USAARL's Aviator Risk Assessment Model (AvRAM) (Harding & Goosey, 2019) based on the model suggested by Barten (1992).

With a WUXGA HMD display source, full-overlapped FOV of 60 by 37.5 degrees are achievable with a Nyquist frequency of 16 cycles/degree. Comparing this resolution to sensor configurations might provide further insight. A 2K sensor, with 2048 X 2048-pixel elements, could achieve 62 degrees squared at the given resolution. This would match fairly well the HMD's horizontal FOV. Increasing the HMD's display source to 4K, manufacturers could achieve the same horizontal FOV with twice the resolution if desired. The half cycle visual angle at twice the resolution would be slightly smaller than the gap/stroke size of a Snellen 20/20 letter.

Based on studies conducted by USAARL and the Army's Night Vision and Electronic Sensors Directorate, in partially overlapped binocular HMDs, pilots prefer a minimum overlap of 40 degrees (unpublished observations and communications). Given this consideration, a WUXGA HMD display source could provide a horizontal FOV of 80 degrees (40 degrees of overlap with two 20-degree monocular FOV).

If current plans call for I^2 and/or forward-looking infrared radar (FLIR) aircraft mounted sensors to be used for primary pilotage instead of night vision goggles (NVGs) (likened to the current AH-64E operational configuration), then possible increases in image resolution should be considered. Under optimum night luminance conditions, current ANVIS models provide for a pilot visual acuity of approximately 20/25. To replicate this resolution while keeping to the minimum 52-degree horizontal FOV recommendation, would require an HMD image source with 1440P resolution (2560 by 1440). This source could provide the needed 48 pixels/degree resolution with a full overlapping FOV of 53 degrees. Of course, for this HMD resolution to be of benefit, the 2K-by-2K sensors would have to be reduced to a 40-degree square FOV or increase the sensor to 4K-by-4K to maintain the 80-degree square FOV mentioned above.

Binocular versus monocular display.

Apache pilots have had vast experience with the IHADSS HDU monocular display and for many of these pilots, visual and perceptual issues resulting from its use have been well chronicled (Behar et al., 1990; Rash et al., 2001, 2004, 2009a, 2009b, 2010, 2015; Harding et al., 2015; Hiatt et al., 2001, 2004). Besides issues associated with eye dominance and the extremely limited eye relief associated with the IHADSS HDU, the combiner lens' notched spectral filter (Harding et al., 1995) aimed at maximizing HMD luminance at the eye causes a difference in ambient luminance and color reaching each eye. Perceptually, it would be beneficial to have the same ambient luminance and color reaching each eye with minimal differential spectral filtering. A binocular HMD with combiner lenses or a reflective visor that has a fairly uniform spectral transmission would solve this issue. Having an option to turn off HMD imagery to one eye or the other would provide pilots the ability to fly with a monocular display if they so choose, but each eye would still see the same ambient scene with identical hues and luminance distributions.

A binocular HMD would eliminate binocular rivalry where image contrast from a monocular HMD waxes and wanes due to suppression from the other eye (Rash et al., 1987). To regain full HMD contrast often requires the temporary closing of the other eye. However, the same symbology presented to both eyes must be held to a minimum to reduce the likelihood of diplopia becoming a perceptual distraction as pilots change their viewing distance (Mclean & Smith, 1987). Even modest changes in viewing distance could cause diplopia. For example, with symbology focused and aligned at infinity a pilot will likely see double symbology when he views objects outside the aircraft from 60 meters or closer.

Luminance and color requirements.

The HMD should have a day mode and a night mode to allow operational functionality under any ambient lighting condition.

Current USAARL guidance on HMD daylight performance is included as an appendix to this document (Appendix A: USAARL Guidance to PM Air Warrior dated September 2018). Appendix B describes the derivation of USAARL developed luminance guidance (Harding et al., 2005, 2016, 2017, 2018, 2019). Appendix C provides revised USAARL daylight luminance guidance. In developing this guidance, the authors found that not only was the luminance of the background important, but the variation in luminance, or spatial complexity of the background, was equally important.

As background complexity is increased, symbology contrast must be increased in order to be distinguished and understood. In years past, government luminance requirements, as specified in solicitations, were based on multiples of a uniform ambient luminance. Unfortunately, we still see solicitations based on these multiples. For example, a recent Navy solicitation (U.S. Government Solicitation N000421-18-R-0091) requires a contrast ratio of 1.2 based on a 10,000 fL ambient scene.

(Note: The 10,000 fL ambient scene is unrealistic and USAARL now uses 6,000 fL in its calculation of HMD luminance requirements, however greater HMD luminance is required at 2,700 fL due to the possibility of increased background complexity at this intermediate ambient level (please see Appendix B for an explanation of this apparent paradox). *Note: the 6,000 fL peak luminance is based on a limit curve that was fit to natural scenes whose peak luminances were set equal to 5,000 fL.* Responding to this solicitation, a vendor proposed a full color HMD with a peak luminance (measured at the eye) of 1,020 fL. Using the vendor's average transmission for their visor and combiner lens, the 10,000 fL ambient luminance would be reduced to 1,366 fL measured at the eye, yielding a contrast of 1.75 ((1020 +1366) ÷ 1366) that exceeded Navy specification. Unfortunately, this luminance is still inadequate for a full color system.

The FLRAA system performance specification (PEO Aviation SFAE-AV-FLRAA, Version 5.0, dated September 21, 2020) also calls for an HMD contrast ratio of 1.2 against bright clouds. As with the Navy solicitation, this luminance requirement is woefully lacking and must be changed.

Using luminance transmission curves for a UH-60 windscreen, and the average values for the vendor's visor and combiner lens, the daylight luminance performance of the vendor's HMD was evaluated using USAARL's AvRAM. The D65 daylight transmission through the combined windscreen, visor, and combiner lens was 11.96%. Using Appendix B equations B7, B8, and B9 for symbology luminance requirements for minimum, average, and good contrast, yielded luminance values of 717, 1,196, and 2,391 fL respectively. Figure 5 shows the luminance output of the HMD for its primary and secondary colors based on sRGB scaling. Note that white, green, yellow, and cyan met the minimum contrast requirements only. Two of the primary colors, red and blue, along with their secondary color magenta, failed to meet even the minimum contrast requirements.

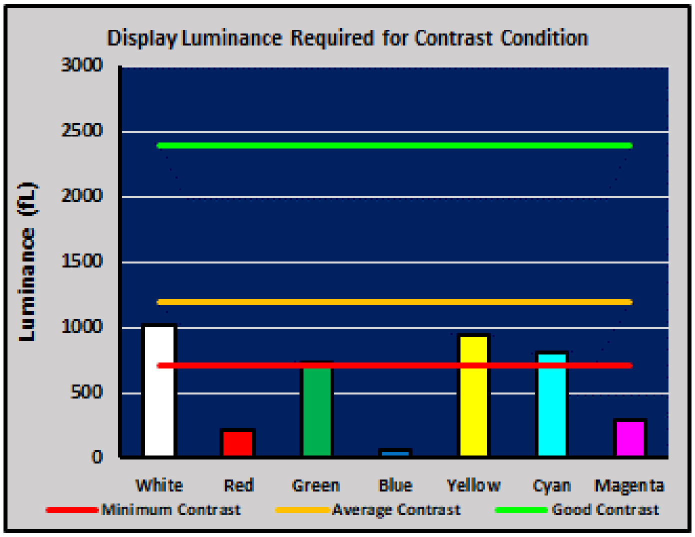

Figure 5. Display luminance from a vendor's HMD (that met government specifications) required to meet minimum, average, and good contrast requirements. Luminance values for primary and secondary colors are based on sRGB scaling.

Figure 6 is an image produced by AvRAM showing the approximate symbology contrast for a normal and slight color vision deficient observer (deuteranomaly score of 55 on Rabin's Cone Contrast Test; score of 55 is required for admission to Army flight school). Note that even against a uniform background, the blue symbols are nearly impossible to detect, let alone identify. Red and magenta letters can be correctly identified against the uniform screen but would quickly become unrecognizable as background complexity began to rise.

It would be useful to examine the contrast of the symbology as judged by Appendix B equations B1, B2, and B3 that define Michelson contrast requirements for minimum, average and good contrast assessments for a uniform field (B_{SD} equals zero). Michelson contrasts of 0.06, 0.18, and 0.36 (the constants in equations B1 through B3) correspond to contrast ratios of 1.128, 1.439, and 2.125 for minimum, average, and good contrast, respectively. The far-right column in Figure 6 depicts each color's contrast ratio against a uniform field and its contrast rating. White (i.e., composite), and cyan meet the good contrast requirement for a uniform field, whereas green and cyan meet the average, and red and magenta meet the minimum contrast condition. Blue fails to meet the minimum contrast requirement with a contrast ratio 1.10. Minimum contrast was defined as all letters that could be deciphered with a little difficulty (see contrast rating definitions in Table B1). Clearly the red letters in Figure 6 are more than a little difficult to decipher.

Figure 6. Letters representing a vendor's HMD symbology with accurate contrast (for a display with gamma = 2.2) against a uniform field based on the data shown in Figure 5. Both the normal and color vision deficient observer (right panel: deuteranomaly score of 55 on the Cone Contrast Test) would have extreme difficulty deciphering red and blue symbology. The far-right panel shows the calculated contrast ratio for each color of symbology for a normal observer. Under each contrast ratio, is the symbology contrast rating against a uniform field based on Appendix B equations B1, B2, and B3.

It is fairly clear that the vendor's full color HMD, that exceeded the government's acquisition specifications for luminance (measured at the eye), would not be operationally usable during bright daylight for showing color coded symbology; at least without significant improvements in luminance gain or increased optical density of the helmet visor or HDU combiner lens. Achieving levels of available luminances for each color in a full color HMD may be difficult, especially for the color blue that accounts for only 7.22% (in an sRGB display system) of a pixel's maximum luminance. To achieve good contrast for blue (2,391 fL required for the vendor's HMD) would require a display capable of producing 33,116 fL at the eye to just meet threshold guidance. As Moffitt and Browne (2019a, 2019b) suggest, using 100% blue plus some portion of green (blue+) that lies between cyan and blue, as an alternative for blue symbology, would reduce the luminance requirement considerably. Figure 7 shows shades of blue achieved by adding increasing amounts of green. For example, the 0.5 patch represents B + 0.5G. In the example chart, calibrated for a display gamma of 2.2, the 0.5 patch is (0, 186, 255). Using the 0.2 patch, which most would agree appears blueish in hue, would increase the blue+ luminance to equal that of the red. In this case, displaying the color red or blue+ would be the deciding factor in calculating required luminances. To achieve the same level for red or blue+ in a sRGB sourced HMD, would require a display capable of producing 13,450 fL of white light. A significant improvement, but still a daunting task for display manufacturers to achieve.

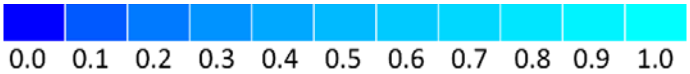

Figure 7. Shades of blue based on 1 part blue plus 0 to 1 part green in steps of 0.1. The left color patch is (0, 0, 255) and rightmost patch is (0, 255, 255). Steps in between 0.0 and 1.0 represent the amount of green that is added to one part of blue. Chart is calibrated for displays with a gamma of 2.2.

Given these considerations, it is critical that developers understand the requirements for see-through displays whose imagery is additive with the ambient scene. We recently reported that symbology colors, even at relatively high contrast, can be easily confused in see-through displays (Harding et al., 2018, 2019). One color can be mistaken for another color which could have serious implications. Based on analysis of luminance requirements, USAARL has slightly lowered the requirements given to Project Manager (PM) Air Warrior in 2018 (see also revised guidance in Appendix C) and further reflect the need for manufacturers to use blue+ for blue symbology. For sRGB displays, blue+ = 1.0 B + 0.2 G. This would equate the luminances for blue and red for symbology purposes. For sensor imagery, there would be no change. Further the improved guidance (Appendix C) sets HMD acquisition specifications for symbology luminance (L_{sym}) to

$$L_{sym}\text{ (threshold)} = 800 \cdot (H_{OT} \div 0.1) \tag{2}$$

$$L_{sym}\text{ (objective)} = 1500 \cdot (H_{OT} \div 0.1) \tag{3}$$

where L_{sym} is in fL and H_{OT} is the combined luminance transmission of D65 skylight for the windscreen, visor, and combiner lens. The threshold represents the midpoint between the observer rated minimum and average contrast symbology conditions and the objective is the midpoint between the observer rated average and good contrast symbology conditions. For an HMD to have sufficient daytime luminance to display all primary and secondary colors (using blue+), then the display should be capable of producing white light (255, 255, 255) at the eye of 3,763 fL for threshold and 7,055 fL for objective (see Table C1 in Appendix C). Of course, these numbers are for a sRGB sourced HMD. Manufacturers may choose to boost red and blue in order to achieve more equal luminance between the primaries; doing so will likely impact color balance and reproduction, so careful attention to detail is critically important (e.g., see white balance note in Table 2).

Eye relief.

USAARL has long recommended 25 mm of physical eye relief (distance between the eye and closest physical part of the combiner, visor, or display lens). This distance will generally allow the unencumbered wearing of spectacles and chemical protective masks as part of an aviators' mission oriented protective posture (MOPP) gear ensemble. Apache aviators know all too well the complications arising due to the insufficient eye relief provided by the IHADSS HDU. Apache aviators were granted permission to fly with contact lenses (Lattimore, 1990; Lattimore & Cornum, 1992) since the HDU did not provide adequate space for normal spectacle usage (McLean & Rash, 1984). Protective masks had to be developed for Apache pilots with specially adapted right-side eyepieces (Crosley et al., 1991). Over the past 20 years, various refractive surgery techniques (e.g., photorefractive keratectomy [PRK], laser-assisted in situ keratomileusis [LASIK]) have been approved for use in Army aviation, further reducing reliance on spectacles for most aircrew (Aeromedical Policy Letter, February 2007). However, it is important to remember that not all aircrew are candidates for contact lenses or refractive surgery; additionally, older aircrew will eventually require refractive correction for reading (presbyopia). Therefore, physical eye relief from optical devices should exceed 25 mm.

Binocular alignment.

In 1986, Herschel Self (Self, 1986) examined the literature to derive human tolerances for vertical and horizontal misalignment of binocular HMDs as well as for rotational and magnification differences. Based on his review, he provided recommended binocular tolerances for partial and full-overlapped HMDs. Self recommended no more than 3.4 arcminutes of vertical misalignment or divergent horizontal misalignment. Greater tolerance is extended for convergent misalignment.

Optical misalignment of binocular devices leads to eye fatigue/strain, diplopia, and other physiological measures (Kalich et al., 2003, 2004a, 2004b; Gavrilescu et al., 2019). Kalich and associates (2003, 2004a, 2004b) found that tolerance limits are greatly affected by visual characteristics of the observer. For example, phorias, accommodative facility, and other optometrics that affect accommodation and vergence had an effect on a subject's ability to tolerate misalignments.

Recommendations

Based on the above review of HMD design principles and other provided references, the following requirements for FVL HMD design are recommended. Note that see-through HMDs can display imagery on a lens in front of the eye (e.g., BAE Q-sight technology using holographic waveguides), reflect imagery off of a combiner lens that is mounted in front of the eye (e.g., IHADSS, HIDSS) or reflect imagery off of a deployed visor (e.g., Thales Top Owl or F35 HMD). In Table 2, references to a combiner lens or combiner are used as generic terms that would apply equally to any of the above configurations.

Being a full color HMD, the optics should provide color correction to eliminate any visible color fringing in display imagery.

The head borne weight and center of a mass of the combined HMD, helmet, and other Aviation Life Support Equipment (ALSE), shall be compliant with the USAARL curve for neck fatigue as shown in Figure 8.

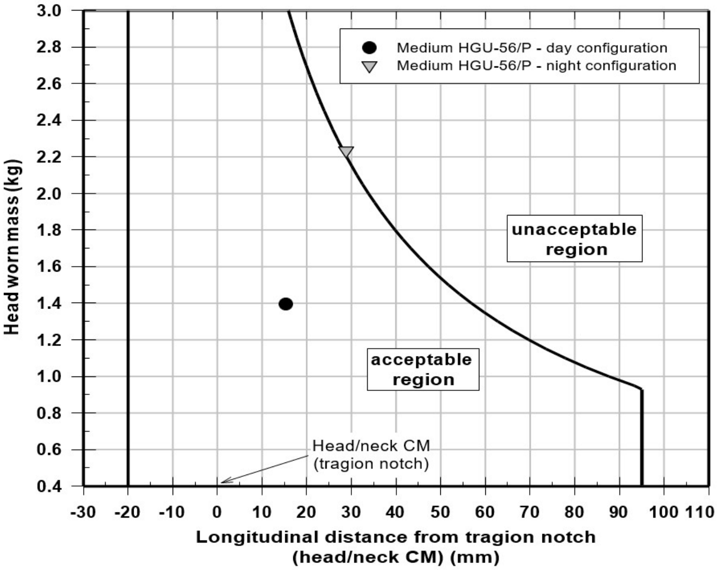

Figure 8. Head worn mass criteria for neck fatigue in helicopter operational environments (X-axis). Data points shown are for two head configuration examples. The day configuration is for a medium HGU-56/P (AIHS) helmet with four-layer TPL, ANVIS mount installed, NVG power connector mounted to visor housing, two hook and pile tape patches on the rear of the helmet, with both visors up, and with 12 inches of communications cord attached. The night configuration is the same as the day but with the ANVIS-6 installed and deployed along with a low-profile battery pack with the batteries installed (taken from the CHMD draft specification dated 16 May 2012).

As examples, two helmet configurations are shown: one for day and one for night operations. Head borne weight and center of mass should also comply with the USAARL neck injury curve as shown in Figure 9, or be frangible (mass shedding) under an acceleration of 10G (±2G). In addition, the frangible component shall not come in contact with the wearer's forehead, eye sockets, or facial regions during separation. This latter provision applies to ANVIS separation from the helmet during hard impacts where the goggles break away from the ANVIS mount. Due to the designed separation, the weight of the goggles and the resulting helmet center of gravity position, which places the helmet outside of the acceptable range, does not disqualify the helmet system thus allowing the night configuration exception (Figure 9).

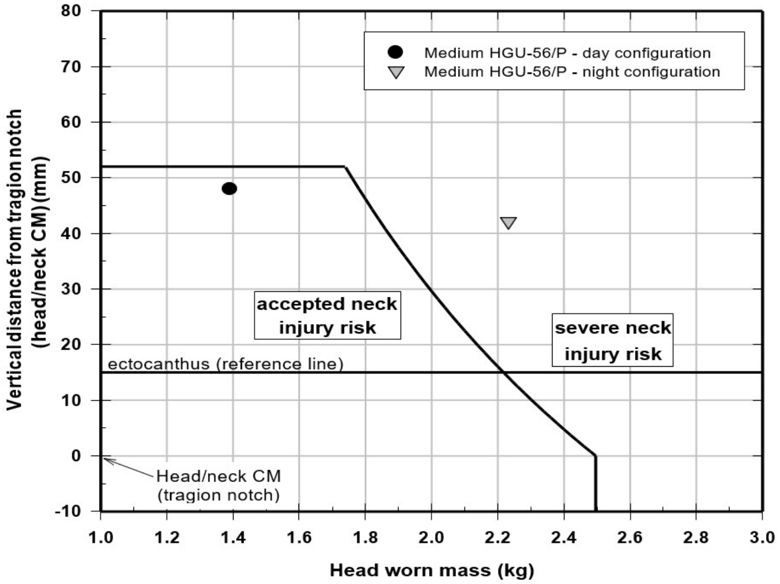

Figure 9. Head worn mass criteria for neck injury in helicopter crash environments (Z-axis). Day and night configurations are the same as described in Figure 8 legend and are shown as examples (taken from CHMD draft specification dated 16 May 2012).

Table 2. Recommended Threshold and Objective Design Guidelines for FVL HMD

Characteristic	Threshold	Objective	Notes
Display type	Binocular	Binocular with monocular capability	
Display format (resolution)	WUXGA (1920 X 1200)	QHD (2560 X 1440)	
FOV	52 degrees with minimum 40-degree overlap	52 degrees with full overlap	
Contrast transfer function	At the Nyquist frequency, Michelson contrast ≥ 0.2 for both vertical and horizontal orientations	At the Nyquist frequency, Michelson contrast ≥ 0.3 for both vertical and horizontal orientations	
Display resolution (Nyquist)	18 cycles/degree (36 pixels/degree; pixel spacing = Snellen line 33)	24 cycles/degree (48 pixels/degree; pixel spacing = Snellen line 25)	

Characteristic	Threshold	Objective	Notes
Display format (color)	Full color display with 6 bits per color	Full color display with 8 bits per color	
Color separation	Minimum separation distance (Δu' and Δv') of 0.25 between each of the primes on the C.I.E. 1976 U.C.S. chromaticity diagram (Figure 10)	Minimum separation distance (Δu' and Δv') of 0.3 between each of the primes on the C.I.E. 1976 U.C.S. chromaticity diagram (Figure 10)	White balance should fall within 0.02 (Δu' and Δv') distance from the D65 locus. (sRGB standard primary color separation distances exceed the objective)
Luminance at the eye (Day mode)	Adjustable luminance (measured at the eye) with a minimum ≤ 10 fL to peak luminance ≥ 800 fL * (H_{OT} ÷ 0.1). Peak luminance applies to red and green primary colors and blue+	Adjustable luminance (measured at the eye) with a minimum ≤ 10 fL to peak luminance ≥ 1,500 fL * (H_{OT} ÷ 0.1). Peak luminance applies to red and green primary colors and blue+	Based on sRGB with blue+ = 1.0 B + 0.2 G (i.e., sufficient green primary where luminance of blue+ ≥ red luminance). H_{OT} = combined D65 luminance transmission of optical elements between eye and ambient scene
Luminance at the eye (Night mode)	Luminance at the eye shall be adjustable from maximum peak luminance of 50 fL to a minimum of 0.01 fL		For backlit image sources, intensity of the backlight must be reduced such that the veiling luminance from a blank screen ≤ 0.01 fL
Luminance transmission	Combiner lens ≥ 60% for D65 and ≥75% for all onboard display systems	Combiner lens ≥ 75% for D65 and for all onboard display systems	
Luminance uniformity	Non-uniformity in luminance ≤ ± (0.5 * FOV diameter (degrees) * 1%)	Non-uniformity in luminance ≤ ± (0.25 * FOV diameter (degrees) * 1%)	Vertical luminance uniformity measures will use the vertical FOV diameter and horizontal luminance uniformity measures will use the horizontal FOV diameter
Flicker/Jitter	No discernable flicker or jitter over entire luminance range of HMD	No discernable flicker or jitter over entire luminance range of HMD	
Physical Eye Relief	≥ 25 mm	≥ 30 mm	

Characteristic	Threshold	Objective	Notes
Eye box or exit pupil diameter	At the physical eye relief of 25 mm, the exit pupil minimum diameter ≥ 12 degrees	At the physical eye relief of 30 mm, the exit pupil minimum diameter ≥ 15 degrees	
Latency	Latency ≤ 1/frame rate (seconds)	Latency ≤ 1/frame rate (seconds)	Frame rate ≥ 50 Hz
Focus	Imagery with fixed focus set at infinity (+0.00 to -0.25 diopter)	Imagery fixed at infinity with user adjustable focus (+0.125 to -1.0 diopter	
Field Curvature	Variation in focus across FOV ≤ ± 0.375 diopter	Variation in focus across FOV ≤ ± 0.250 diopter	
Day/Night transition	Able to transition between day and night capabilities with no more than two hardware configuration changes	Able to transition between day and night capabilities with no more than one hardware configuration changes	
Display Distortion	Residual distortion shall be less than 4%	Residual distortion shall be less than 3%	
ANVIS Compatibility	If used in conjunction with ANVIS goggles, the middle of the HDU image formation shall coincide with the center of the ANVIS FOV (Image alignment can be accomplished with HDU image horizontal and vertical adjustments)	If used in conjunction with ANVIS goggles, the middle of the HDU image formation shall coincide with the center of the ANVIS FOV (Image alignment can be accomplished with HDU image horizontal and vertical adjustments)	At this writing, it is unclear if FVL aircraft will forgo the use of head-mounted NVGs
Interpupillary distance adjustment	58-72 mm	55-75 mm	
Combiner Distortion (see-through)	MIL-STD-43511D Criteria	MIL-STD-43511D Criteria	Combiner see-through distortion should be < than helmet visor
Prismatic Deviation (combiner see-through)	Horizontal and vertical prismatic deviation ≤ 0.18 prism diopter BASE IN and prismatic deviation ≤ 0.25 diopter BASE OUT	Horizontal and vertical prismatic deviation ≤ 0.15 prism diopter BASE IN and prismatic deviation ≤ 0.20 diopter BASE OUT	Prismatic deviation stated herein includes the inherent prismatic power resulting from nonparallel surfaces of the material and dissimilar curvature between the critical areas

Characteristic	Threshold	Objective	Notes
Binocular Alignment (vertical)	Misalignment between left and right optical axes ≤ 3.4 arcminutes	Misalignment between left and right optical axes ≤ 2.5 arcminutes	Over the entire IPD adjustable range
Binocular Alignment (horizontal)	Misalignment between left and right optical axes ≤ 3.4 arcminutes	Misalignment between left and right optical axes ≤ 2.5 arcminutes	
Binocular Alignment (rotational)	Misalignment between left and right optical axes ≤ 3.4 arcminutes	Misalignment between left and right optical axes ≤ 2.5 arcminutes	
Binocular Alignment (magnification)	Less than 2 percent	Less than 1 percent	The difference in display image magnification between right and left images
Interpupillary distance adjustment	58-72 mm	55-75 mm	
Combiner Distortion (see-through)	MIL-STD-43511D Criteria	MIL-STD-43511D Criteria	Combiner see-through distortion should be < than helmet visor
Prismatic Deviation (combiner see-through)	Horizontal and vertical prismatic deviation ≤ 0.18 prism diopter BASE IN and prismatic deviation ≤ 0.25 diopter BASE OUT	Horizontal and vertical prismatic deviation ≤ 0.15 prism diopter BASE IN and prismatic deviation ≤ 0.20 diopter BASE OUT	Prismatic deviation stated herein includes the inherent prismatic power resulting from nonparallel surfaces of the material and dissimilar curvature between the critical areas
Binocular Alignment (vertical)	Misalignment between left and right optical axes ≤ 3.4 arcminutes	Misalignment between left and right optical axes ≤ 2.5 arcminutes	Over the entire IPD adjustable range
Binocular Alignment (horizontal)	Misalignment between left and right optical axes ≤ 3.4 arcminutes	Misalignment between left and right optical axes ≤ 2.5 arcminutes	
Binocular Alignment (rotational)	Misalignment between left and right optical axes ≤ 3.4 arcminutes	Misalignment between left and right optical axes ≤ 2.5 arcminutes	
Binocular Alignment (magnification)	Less than 2 percent	Less than 1 percent	The difference in display image magnification between right and left images

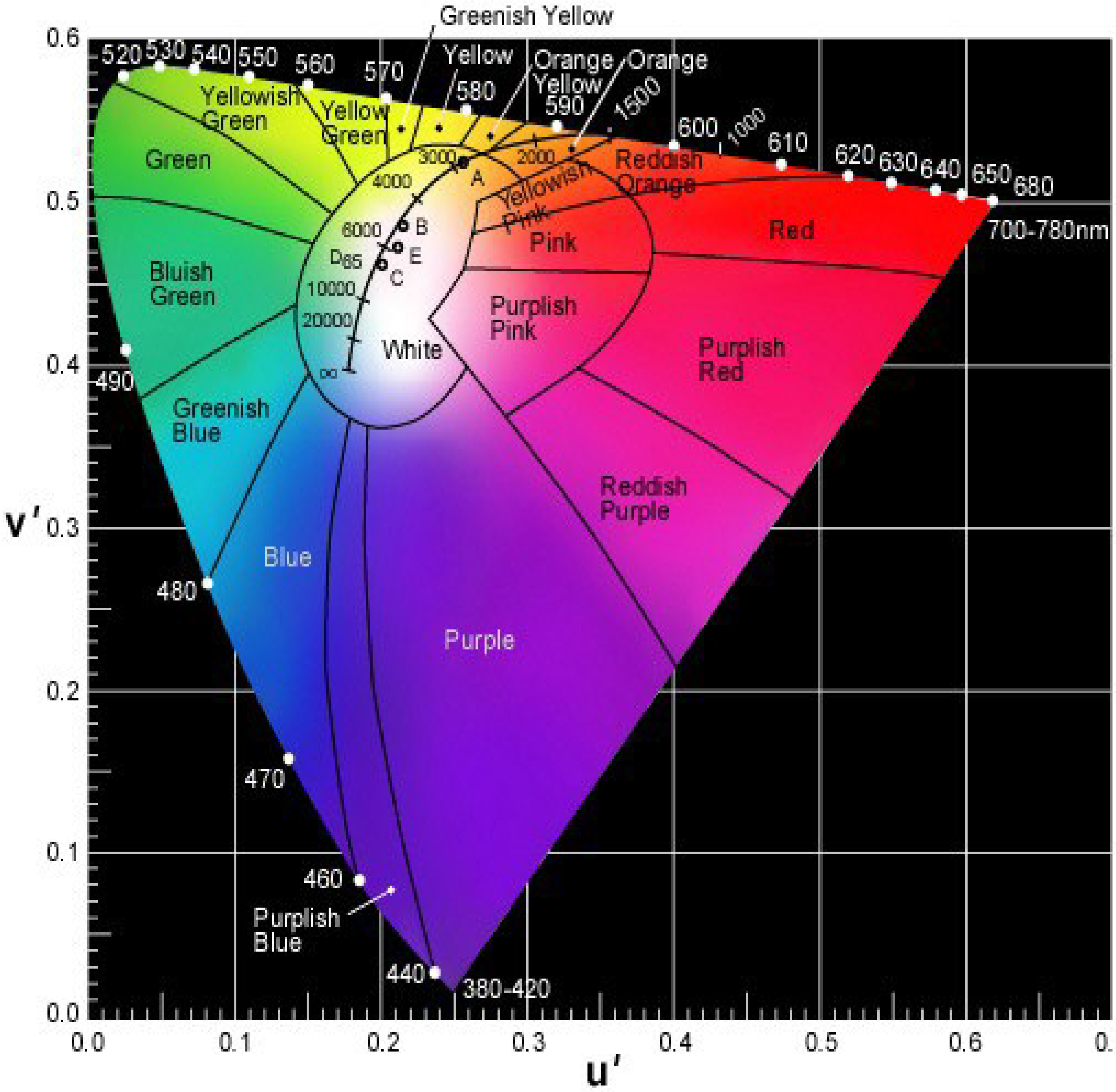

Figure 10. CIE (Commission Internationale de l'éclairage) 1976 Uniform Color Space (UCS) chromaticity diagram.

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Appendix A. USAARL Guidance to PM Air Warrior (September 2018)

Daylight Luminance Requirements for See-through Displays

Daylight luminance requirements for see-through display systems based on an average optical density of 1.0 for windscreen, visor, and HMD combiner lens*:

Threshold (based on average contrast requirements): The HMD luminance at the eye shall be a minimum of 1,000 fL for each symbology color.

Objective (based on good contrast requirements): The HMD luminance at the eye shall be a minimum of 2,500 fL for each symbology color. For a full color system whose display source is based on sRGB scaling, the table below provides luminance requirements for each primary and secondary color as well as white.

Table A1. Calculated See-through HMD Display luminances (fL) For a Color Normal Observer** Based on the Seven Symbology Colors (primaries, secondaries, and white). Values assume a combined optical density for windscreen, visor, and HMD combiner lens of 1.0. Values are based on the percent contribution of the three primaries to overall pixel luminance based on sRGB scaling.

percentage of white	Red	Green	Blue	Yellow	Cyan	Magenta	White
	21.26%	71.52%	7.22%	92.78%	78.74%	28.48%	100.00%
Red = 2,500 fL	2,500	8,410	849	10,910	9,259	3,349	11,759
Green = 2,500 fL	743	2,500	252	3,243	2,752	996	3,496
Blue = 2,500 fL	7,361	24,765	2,500	32,126	27,265	9,861	34,626
Yellow = 2,500 fL	573	1,927	195	2,500	2,122	767	2,695
Cyan = 2,500 fL	675	2,271	229	2,946	2,500	904	3,175
Magenta = 2,500 fL	1,866	6,278	634	8,144	6,912	2,500	8,778
White =2,500 fL	765	2,575	260	3,340	2,835	1,025	2,500

* Assumes the HMD is mounted behind the helmet visor

** For color deficient aviators, these luminance values may need to be increased by about 25%.

Data based on:

Harding, T. H., Rash, C. E., Lattimore, M. R., Statz, J., & Martin, J. S. (2016). Perceptual issues for color helmet- mounted displays: luminance and color contrast requirements. *Proc. SPIE 9839, 15*, 1–10.

Harding, T. H. & Rash, C. E. (2017). Daylight luminance requirements for full-color, see-through, helmet- mounted display systems. *Opt. Eng. 56*(5), 051404.

As amended and corrected by:

Harding, T. H., Hovis, J. K., Rash, C. E., Smolek, M. K., & Lattimore, M. R. (2018). HMD daylight symbology: Color discrimination modeling. *Proc. SPIE 10642, 03*, 1–14.

Harding, T. H., Hovis, J. K., Rash, C. E., Smolek, M. K., & Lattimore, M. R.(2019). Modeling perceptual color confusion of HMD symbology. *Journal of Optical Engineering, 58*(5), 051804 1–10.

Appendix B. Derivation of USAARL Guidance for Daylight Luminance Requirements for See-through Displays

As an initial step in defining the luminance requirements for daylight symbology, Harding et al. (2005) reported on a human experiment where subjects evaluated the quality of HMD symbology overlaid over eight static natural scenes, one artificially created complex image, and a uniform field (Figure B1). For each background image, 20 contrast correct images of overlaid white symbology were evaluated using a seven-point rating scale (Table B1). The overlaid symbology shown in Figure B2 was created by use of a software model that applied appropriate luminance scaling to yield symbology that has been added to the background image. In this experiment, the complexity of the background image was of paramount importance when determining the minimum luminance requirements for see-through symbology.

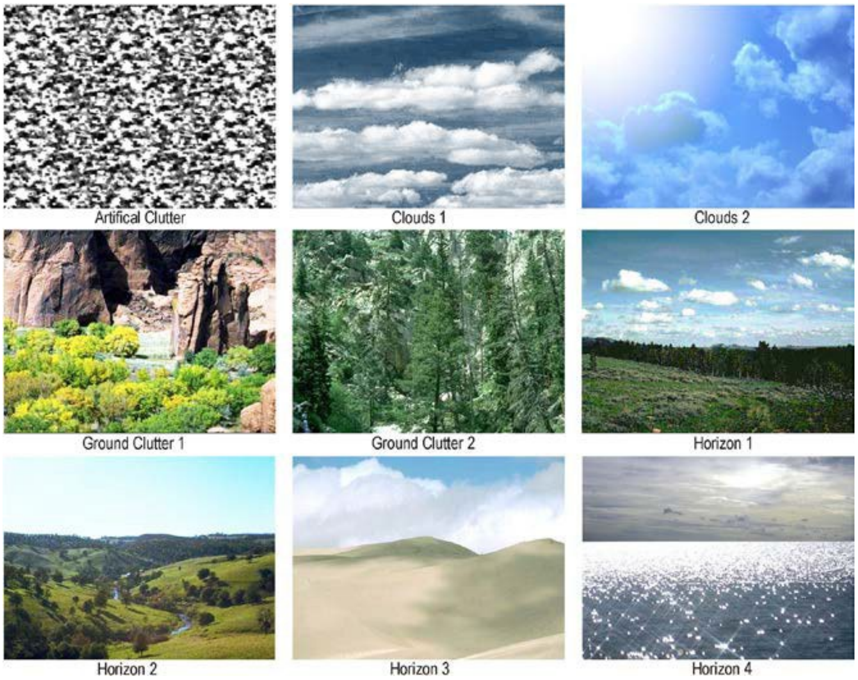

Figure B1. Nine of the ten images used to evaluate the quality of overlaid symbology. The tenth image was a uniform field. Image from Harding et al. (2005).

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Table B1. Rating Scale and Description of Ratings Given to Subject in Harding et al. (2005)

Rating	Quality of Symbology	Description of Rating
7	Excellent	All letters and symbols are easily seen with high contrast
6	Very Good	All letters and symbols are easily seen with good contrast
5	Good	All letters and symbols can be seen with reduced contrast
4	Adequate	All letters and symbols can be deciphered with a little difficulty
3	Poor	Letters and symbols can barely be detected and some letters or symbols are very difficult to see
2	Not adequate	Some of the letters and symbols cannot be seen.
1	Not usable	Difficulty to recognize that symbology is present

Average contrasts were calculated for each of the 200 images, and the contrasts varied widely depending on the background images. The average Michelson contrast was calculated for each of the images and these contrasts were plotted as a function of the average observer ratings. Figure B2 shows the results for all 10 of the background images. Least square power functions were fit to each image set ($R^2 > 95\%$ based on curves fit to data points at or below an observer rating of 6.5). For each background image, observer ratings of 4, 5, and 6 were calculated from the curve fits. For six of the images, observer ratings of 4 or lower were not observed, and extending the curve fits allowed calculations of the minimum contrast rating (i.e., see data for images "cloud 1," "cloud 2," "horizon 2," "horizon 3," "horizon 4," and "uniform" in Figure B2).

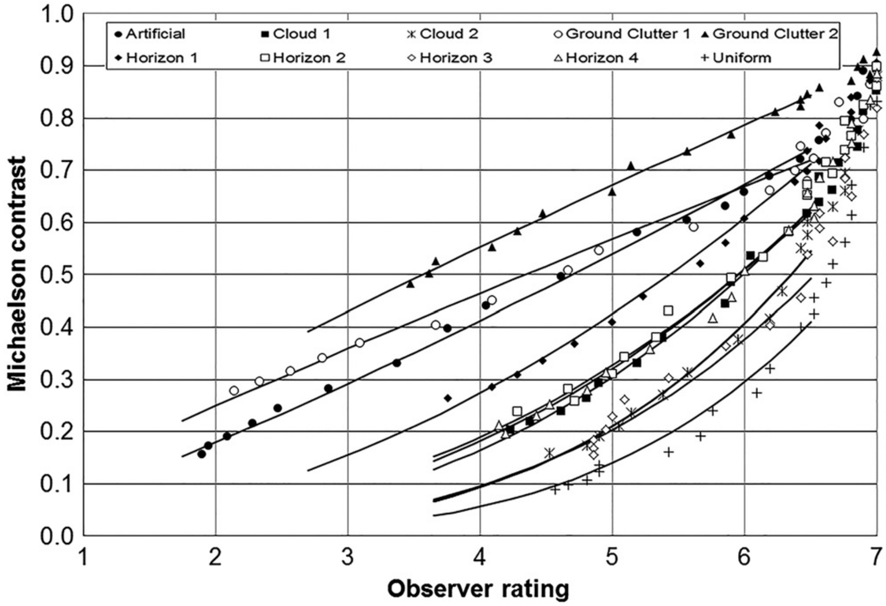

Figure B2. Contrast plotted as a function of observer ratings for the 10 background images. The solid curves are power functions fit to the data.

To assess the relationship between the contrast required for an observer rating of 4, 5, and 6, observer data for each of the images were averaged and plotted. Figure B3 shows the contrast requirements for each of the 10 images as a function of B_{SD} (percent standard deviation of the background). For purposes of this discussion, we will term observer ratings of 4, 5, and 6 as minimum contrast, average contrast, and good contrast, respectively. Linear curves of the same slope were fit to each of the ratings in Figure B3 and are given below:

$$\text{Minimum contrast} = 0.06 + 0.58\, B_{SD} \qquad R^2 = 87.8\% \qquad \text{(B1)}$$

$$\text{Average contrast} = 0.18 + 0.58\, B_{SD} \qquad R^2 = 89.3\% \qquad \text{(B2)}$$

$$\text{Good contrast} = 0.36 + 0.58\, B_{SD} \qquad R^2 = 83.6\% \qquad \text{(B3)}$$

Harding et al. (2016) and Harding and Rash (2017) derived an envelope equation (B4) that described the highest probable amount of luminance complexity contained within a natural scene as a function of ambient luminance. To evaluate scene complexity within a background image, the peak luminance within each image was set equal to 5,000 fL using sRGB scaling. In sRGB scaling, a pixel with RGB values of 255, 255, and 255, the red subpixel contributes 21.26%, the green subpixel contributes 71.52%, and the blue subpixel contributes 7.22% of the total pixel luminance. Luminance complexity, the standard deviation of pixel luminances, was calculated for small patches of pixels (e.g., 10 by 10) within the background scenes and plotted in Figure B4. Note that the complexity values, calculated from natural scenes, extend up to 5,000 fL whereas the limit curve extends to 6,000 fL. Because of this, USAARL uses the 6,000 fL figure as the maximum peak daylight luminance. However, it is of little consequence, because maximum symbology luminance is required for an intermediate level of luminance (about 2,700 fL) due to the possibility of higher background complexities at this level (Figure B5).

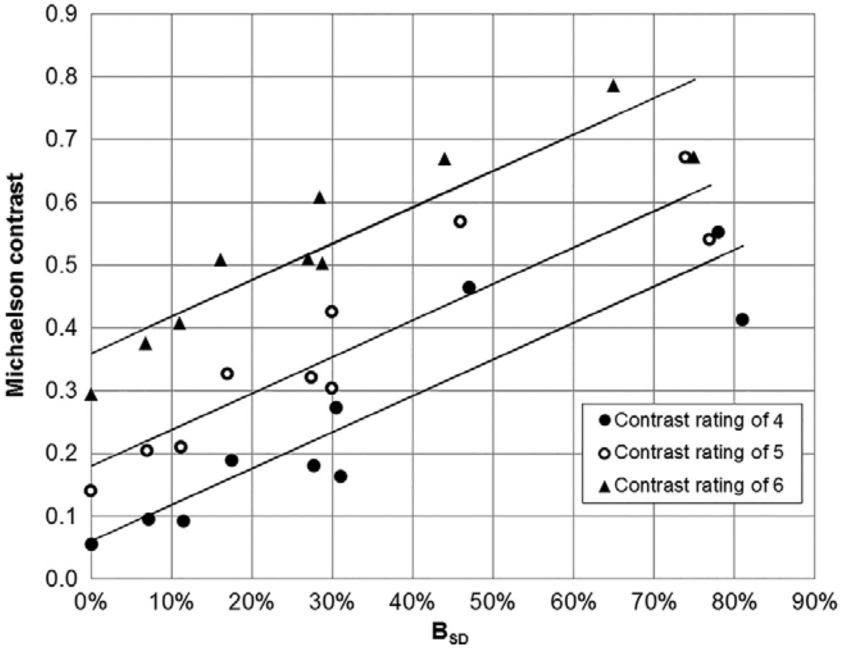

Figure B3. Contrast requirements as a function of BSD for observer ratings of 4, 5, and 6. Each set of data has 10 data points representing the 10 background images. The straight lines are linear fits to each of the observer ratings (equations 1-3).

Greater than 99% of the calculated percent standard deviations fell below the curve that described the envelope (equation B4):

$$B_{SD} = [-1.0 \ln (L_B) + 8.7] \cdot 100\% \qquad \text{over the range 1 to 6,000 fL,} \qquad (B4)$$

where L_B is the background ambient luminance. The authors analyzed additional highly complex background images and found the envelope curve to be robust.

To calculate symbology luminance (L_{sym}) in an image, we used the following equations

$$L_{sym} = L_{max} - L_{min} \qquad (B5)$$

where L_{max} equals the symbology luminance from the HMD plus the background luminance and L_{min} equals the background luminance or ambient scene luminance. Thus to calculate Michelson contrast we have

$$(L_{max} - L_{min}) \div (L_{max} + L_{min}) = (L_{sym} \div (L_{sym} + 2 \cdot L_{min})) \qquad (B6)$$

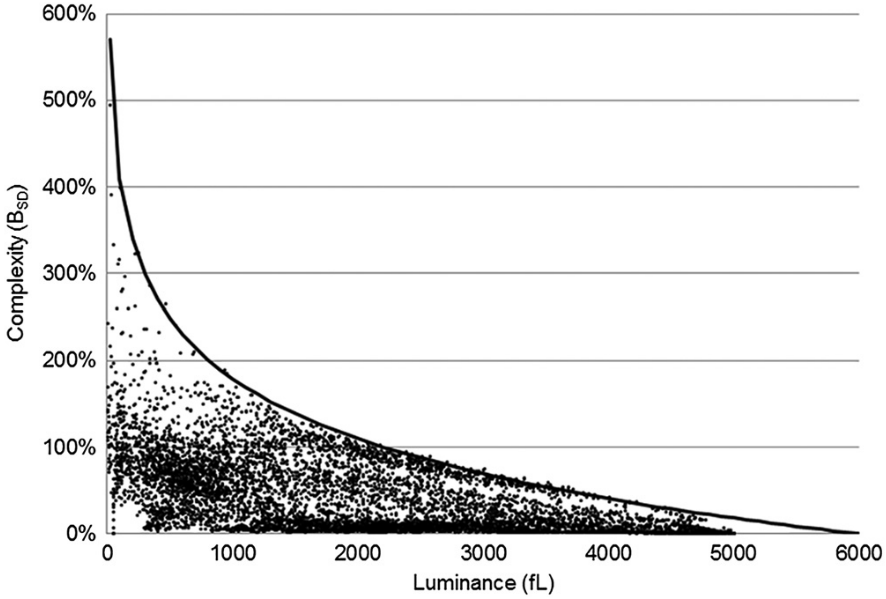

Figure B4. Scatter plot of small area analysis of each of eight natural scenes and one artificial high complexity scene used to evaluate the quality of overlaid symbology. The solid curve is from equation 1. From Harding and Rash, 2017.

When calculating contrast using equations B1 through B3 for low luminance and high spatial complexity as specified in equation 4, Michelson contrast values will exceed 1.0 which is clearly not possible. Thus it is necessary to set a cap on Michaelson contrast. In the original research, the average B_{SD} for the eight natural scenes and one artificial background did not exceed 80%. Setting B_{SD} to 80% in equations 1 through 3 provides a contrast cap of 0.524, 0.644, and 0.824 for minimum, average, and good contrast, respectively. Using these maximum contrast caps, Figure B5 shows the minimum, average and good contrast plotted as a function of the limit curve described in equation 4.

Note that all three contrast conditions peak at an intermediate level of ambient luminance owing to the effect of background complexity on observed contrast. Using the maximum luminances for the minimum, average, and good contrast conditions provides a basis for establishing daylight luminance requirements for HMD symbology. Of course, these values will be reduced based on optical densities of windscreens, visors, and HMD combiner lenses. The following three equations define the daylight luminance requirements (fL) for minimum, average, and good contrast based on a peak daylight sky luminance of 6,000 fL:

$$L_{sym} \text{ (minimum)} = 593 \cdot (H_{OT} \div 0.1) \qquad 7{,}055 \qquad \text{(B7)}$$

$$L_{sym} \text{ (average)} = 974 \cdot (H_{OT} \div 0.1) \qquad \text{(B8)}$$

$$L_{sym} \text{ (good)} = 2{,}020 \cdot (H_{OT} \div 0.1) \qquad \text{(B9)}$$

where H_{OT} is the combined hardware optical luminance transmission that will be applied to the ambient scene. In calculating luminance transmission, standard D65 skylight (sky with a color temperature of 6500° Kelvin) should be used. For the IHADSS HDU, optical density will be the sum of the densities for the windscreen, tinted visor, and HMD combiner lens. Thus for a combined luminance transmission of 0.1 (optical density of 1.0) the second half of each equation becomes unity. Thus for hardware luminance transmissions greater than 0.1, the luminance will be higher than the constants in each equation.

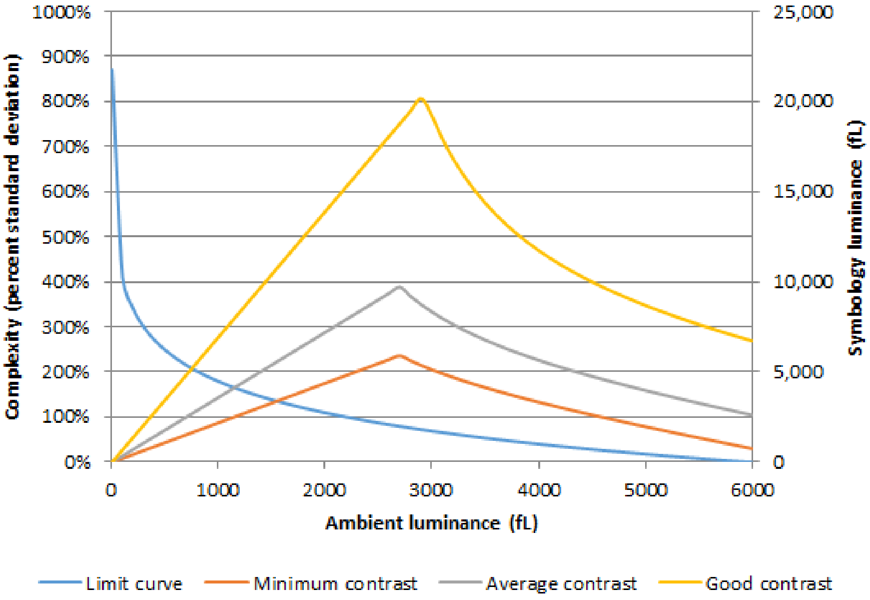

Figure B5. Applying equations 1, 2, and 3 to the limit curve. The right vertical axis applies to the minimum, average, and good contrast curves. The linear rise in the luminance curves was due to the B_{SD} limits placed on each contrast condition (see text for details).

Rounding the constants in equations B7 to B9 to the nearest 100 yields the following simpler equations

$$L_{sym} \text{ (minimum)} = 600 \cdot (H_{OT} \div 0.1) \qquad \text{(B7)}$$

$$L_{sym} \text{ (average)} = 1{,}000 \cdot (H_{OT} \div 0.1) \qquad \text{(B8)}$$

$$L_{sym}\ (\text{good}) = 2{,}000 \cdot (H_{OT} \div 0.1) \qquad \text{(B9)}$$

Compare USAARL's 2018 HMD daylight luminance guidance to PM Air Warrior (Appendix A) with equations B8 and B9. The threshold guidance of 1,000 fL is in agreement with equation B8. However, the objective guidance of 2,500 fL exceeds equation B9 and should be reduced.

Achieving these levels of available luminances for each color in a full color HMD may be difficult, especially for the color blue that can account for only 7.22% of a pixel's maximum luminance. To achieve 1,000 fL of blue would require a display capable of producing 13,850 fL at the eye to just meet threshold guidance. As Moffitt and Browne (2019a, 2019b) suggest, using 100% blue and 50% green that lies between cyan and blue as an alternative to blue would reduce the luminance requirement considerably.

In the text of the main document, we argue for a 20% addition of green which would equate the luminances for red and blue+. Now displaying the color red would be the deciding factor in calculating required luminances. To achieve 1,000 fL of red in a sRGB sourced HMD, would require a display capable of producing 4,704 fL of white light.

Appendix C. Revised USAARL Guidance on Daylight Luminance Requirements for See-through Displays

The following daylight luminance requirements are based on equations derived from observer ratings of the quality of symbology mixed with natural and artificial scenes. Three equations were derived for minimum contrast, average contrast, and good contrast (see Appendix B):

L_{sym} (minimum) = $600 \cdot (H_{OT} \div 0.1)$

L_{sym} (average) = $1{,}000 \cdot (H_{OT} \div 0.1)$

L_{sym} (good) = $2{,}000 \cdot (H_{OT} \div 0.1)$

where L_{sym} is the symbology luminance in fL and H_{OT} is the combined D65 luminance transmission through the windscreen, visor, and combiner lens. Threshold luminance is the average of the minimum and average L_{sym} requirement and the objective luminance is the average of the average and good L_{sym} requirement.

The revised daylight luminance requirements (fL) for see-through display systems, as measured at the eye, based on an average optical density of 1.0 for windscreen, tinted visor, and HMD combiner lens* are

L_{sym} (threshold) = $800 \cdot (H_{OT} \div 0.1)$

L_{sym} (objective) = $1500 \cdot (H_{OT} \div 0.1)$

The threshold and objective guidelines are for a full color system whose display source is based on sRGB scaling. The table below (Table C1) provides the approximate luminance requirements for each primary and secondary color as well as white. Table C1 assumes blue+ will be used to display blue symbology. Blue+ = B + 0.2 G. For example:

Blue+ = (0, 51, 255) for a display gamma of 1.0

Blue+ = (0, 123, 255) for a display gamma of 2.2

Table C1. Calculated See-through HMD Display Luminances (fL) For a Color Normal Observer Based on the Seven Symbology Colors (primaries, secondaries, and white) with Blue Symbology Displayed as blue+ = (B + 0.2 G). Values assume a combined optical density for windscreen, visor, and HMD combiner lens of 1.0. Values are based on the percent contribution of the three primaries to overall pixel luminance based on sRGB scaling.

Percentage of white	**Red** 21.26%	**Green** 71.52%	**Blue** 7.22%	**Blue+** 21.52%	**Yellow** 92.78%	**Cyan** 78.74%	**Magenta** 28.48%	**White** 100.00%
Threshold ≥ 800 fL	800	2,691	272	810	3,491	2,963	1,072	3,763
Objective ≥ 1,500 fL	1,500	5,046	509	1,518	6,546	5,555	2,009	7,055

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