AFRL-RH-WP-TP-2011-0012

EVALUATION OF ANTI-GLARE APPLICATIONS FOR A TACTICAL HELMET-MOUNTED DISPLAY

Jason L. Roll
Oak Ridge Associated Universities

Noel J. M. Trew, Paul Havig
Decision Making Division

Matthew R. Geis
Integration & Operations Division

MARCH 2012

Distribution A: Approved for public release; distribution unlimited.

AIR FORCE RESEARCH LABORATORY
711 HUMAN PERFORMANCE WING,
HUMAN EFFECTIVENESS DIRECTORATE,
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RH-WP-TP-2011-0012 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//**signed//**
GREGRORY M. BURNETT
Program Manager
Battlespace Acoustics Branch

//signed//
WILLIAM T. NELSON
Chief, Battlespace Acoustics Branch
Decision Making Division

//**signed//**
MICHAEL A. STROPKI
Decision Making Division
Human Effectiveness Directorate
711 Human Performance Wing

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
01-03-12	INTERIM	1 October 2010 – 30 March 2012

4. TITLE AND SUBTITLE
EVALUATION OF ANTI-GLARE APPLICATIONS FOR A TACTICAL HELMET-MOUNTED DISPLAY

5a. CONTRACT NUMBER IN-HOUSE
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 63231F

6. AUTHOR(S)
Jason L. Roll*, Noel J. M. Trew**, Matthew R. Gies**, Paul R. Havig**

5d. PROJECT NUMBER 2830
5e. TASK NUMBER 16
5f. WORK UNIT NUMBER 28301609

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Oak Ridge Associated Universities*
4692 Millennium Drive
Belcamp, MD 21017

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Materiel Command**
Air Force Research Laboratory
711 Human Performance Wing
Human Effectiveness Directorate
Decision Making Division
Battlespace Acoustics Branch
Wright-Patterson Air Force Base, OH 45433

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
711 HPW/RHCB

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RH-WP-TP-2011-0012

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
88 ABW Cleared 04/05/2011; 88ABW-2011-2016.

14. ABSTRACT:
Non see-through, monocular helmet mounted displays (HMDs) provide warfighters with unprecedented amounts of information at a glance. The US Air Force recognizes their usefulness, and has included such an HMD as part of a kit for ground-based, Battlefield Airmen. Despite their many advantages, non-see-through HMDs occlude a large portion of the visual field when worn as designed, directly in front of the eye. To address this limitation, operators have chosen to wear it just above the cheek, angled up toward the eye. However, wearing the HMD in this position exposes the display to glare, causing a potential viewing problem. In order to address this problem, we tested several film and HMD hood applications for their effect on glare. The first experiment objectively examined the amount of light reflected off the display with each application in a controlled environment. The second experiment used human participants to subjectively evaluate display readability/legibility with each film and HMD hood covering under normal office lighting and under a simulated sunlight condition.

15. SUBJECT TERMS
Helmet-Mounted Display, HMD, Glare, Anti-Reflective, Hood

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			Gregory Burnett
Unclassified	Unclassified	Unclassified	SAR	15	19b. TELEPHONE NUMBER *(Include Area Code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

THIS PAGE INTENTIONALLY LEFT BLANK.

Evaluation of anti-glare applications for a tactical helmet-mounted display

Jason L. Roll[1], Noel J. M. Trew[2], Matthew R. Geis[3], Paul R. Havig[4]
[1]Oak Ridge Associated Universities, 4692 Millennium Drive, Belcamp, MD 21017
[2]711HPW/RHCB, 2610 Seventh Street, Wright-Patterson AFB, OH, USA 45433
[3]AFRL/RXOF, 2977 Hobson Way, Wright-Patterson AFB, OH, USA 45433
[4]711HPW/RHCV, 2255 H Street, Wright-Patterson AFB, OH, USA, 45433

ABSTRACT

Non see-through, monocular helmet mounted displays (HMDs) provide warfighters with unprecedented amounts of information at a glance. The US Air Force recognizes their usefulness, and has included such an HMD as part of a kit for ground-based, Battlefield Airmen. Despite their many advantages, non see-through HMDs occlude a large portion of the visual field when worn as designed, directly in front of the eye. To address this limitation, operators have chosen to wear it just above the cheek, angled up toward the eye. However, wearing the HMD in this position exposes the display to glare, causing a potential viewing problem. In order to address this problem, we tested several film and HMD hood applications for their effect on glare. The first experiment objectively examined the amount of light reflected off the display with each application in a controlled environment. The second experiment used human participants to subjectively evaluate display readability/legibility with each film and HMD hood covering under normal office lighting and under a simulated sunlight condition. In this test paradigm, participants had to correctly identify different icons on a map and different words on a white background. Our results indicate that though some applications do reduce glare, they do not significantly improve the HMD's readability/legibility compared with an uncovered screen. This suggests that these post-production modifications will not completely solve this problem and underscores the importance of employing a user-centered approach early in the design cycle to determine an operator's use-case before manufacturing an HMD for a particular user community.

Keywords: HMD, Glare, Anti-Reflective, Hood

1. INTRODUCTION

US Air Force Battlefield Airmen are at the tip of America's combat edge. These dismounted, ground-based operators perform a broad range of missions in support of US air assets. While primarily responsible for establishing forward airfields in hostile territory and performing air traffic control at those sites, they are frequently tasked to aid other ground units by coordinating Close Air Support (CAS). During CAS missions, the operator must maintain situation awareness and organize information about the battlespace in a way that allows him to engage the enemy while keeping non-combatants out of harm's way. They must be able to perform this function flawlessly, even while under the pressures of enemy contact.

To this end, the Battlefield Air Operations (BAO) Kit was created in 2004 to provide these Battlefield Airmen with a digital way to represent and manage data about their operational environment and tactical situation[1]. The centerpiece of this kit was a computer loaded with a geographic information system and a suite of targeting applications. Because of the nature of their job, the computer was designed to provide the dismounted soldier with useful data about the tactical environment and also withstand the extremes of their operational environment (i.e. weather, terrain, concussive forces). More importantly, the information had to be presented to the soldier in a manner that did not interfere with the user's ability to sense the immediate environment. It does the operator no good to see a potential target 5 miles away if that keeps him from seeing the sniper 200 yards away.

Therefore, the current generation of the BAO kit includes a monocular HMD (i.e. the Vuzix Tac-Eye LT), connected to a small wearable computer (SWC)[1]. This HMD can be attached to a boom mount on the helmet and worn over either eye, permitting the operator to look at the display for a quick reference to his GIS and other applications. This allows him to maintain tactical awareness, to analyze data and to communicate the results of his analysis to other friendly forces. All this can be performed on the move, without the need for the operator to drop his rucksack to pull out a traditional ruggedized laptop.

When the HMD is worn to optimize viewing potential, as it was designed, it partially occludes the visual field of the operator, which in turn degrades battlefield situation awareness. Therefore, the operators have chosen to wear the device just above the maxilla/zygomatic bone, angled up towards their eye so they may reference it like a car's dashboard (see Figure 1). Wearing the HMD in this position introduces another impediment in the form of glare as sunlight is reflected into the user's eye. Since operators can be expected to perform their missions at any time of day, it is essential that a solution for this impediment be found.

Figure 1. Preferred wearing position of HMD ("dashboard" position)

The purpose of this research is to find a possible solution to the glare problem through a comparison of several film coverings and HMD hoods. This glare problem not only affects the operator's ability to view the displayed image from the HMD, it also makes it difficult to see anything with that eye. The Lighting Handbook of the Illuminating Engineering Society of North America[2] defines glare as "the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility". Glare can be further classified into two types: disability glare and discomfort glare[3]. Disability glare occurs when light is scattered in the eye, resulting in the redirection of visibility and visual performance[3]. When an individual experiences disability glare, they usually recognize an immediate reduction in their ability to see. To combat this inability to see, they will attempt to shade the source of the light or physically change their visual position. An example of disability glare would be the high-beam headlights of an on-coming car shinning through a driver's windshield on a dark night. This light would result in the reduction of the driver's visibility of the road ahead. Discomfort glare occurs when the presence of bright light causes the sensation of pain and discomfort[3]. Discomfort glare generally does not cause a reduction of visibility and visual performance. An example of discomfort glare would be high-beam headlights shining into a driver's rear-view mirror from a car directly behind them. This situation generally does not cause a reduction in the driver's visibility of the road ahead, but can cause the sensations of pain and discomfort.

The type of glare experienced by this user population appears to be disability glare, as they have expressed their inability to see the displayed image through the HMD's viewing panel. The cause of this glare can be attributed to the angle at which the operator chooses to wear the HMD as well as the current design of the HMD. Obtained through an interview of several operators, the preferred wearing position of the HMD is angled up towards the eye, instead of in the direct line of sight of the eye. The reasoning for this position is to prevent a complete obstruction of that eye's view of the surroundings. However, the HMD as currently designed, should be worn directly in front of one of the eyes. In this position, sunlight glare would not be experienced, as the light would not have the opportunity to enter the HMD in the first place. Considering the user's concern for situation awareness, this position is not ideal.

The Vuzix Tac Eye Lt. incorporates a beam splitting element that directs the light from the organic light-emitted diode (OLED) display to a concave mirror, which in turn directs the enlarged OLED image into the user's eye. When the HMD is worn angled up towards the eye instead of directly in front of the eye as it was designed, sunlight enters through the viewing panel and is reflected off the beam splitter back into the user's eye. This redirected light is known as veiling glare, and is a form of disability glare[4]. This glare can wash out the displayed image, rendering the HMD useless.

There are a number of films that can be applied to the surface of the HMD's viewing panel that may prevent external light from entering the HMD and thus reducing the effect of glare. One of the most common types of films used to combat glare is anti-reflective (AR) film. AR film acts as a light absorber by altering the refractive index of the viewing panel's surface[4]. Because of this change in the refractive index, when external light hits the panel it is not permitted to enter the HMD to cause veiling glare. The film's composition produces a destructive interference of the light within the film causing reflections to cancel each other out[5]. Additionally, AR film should not diffuse the light from the HMD's displayed image. Microlouver film might also be a solution to reduce the amount of external light reflected back into the eye. Microlouver film contains what resemble tiny Venetian blinds that run perpendicular to the surface of the film[6]. Any external light that hits the film from the left or the right will be reflected away from the film in the same direction, and thus cannot enter the HMD to cause veiling glare. The downside to using this type of film is that not only would it limit the angle at which the external light could enter the HMD, it would also limit the angle at which the light from the displayed image could exit the HMD[6]. The ability of light from the displayed image to exit through the film would be subject to the same constraints as the external light attempting to enter through the film. This would mean that although the film may be successful in preventing the external light from entering the HMD, it does not guarantee that the light from the displayed image will be able to exit through the film for the operator to see. Polarizing film is another option that could potentially be used to prevent sunlight from entering the HMD, and thus preventing the veiling glare. Polarizing film limits which wavelength of light the user sees[7]. The sunlight wavelength entering the polarizing film would be eliminated within the film, and thus the effect of glare is prevented. Additionally, the wavelength of light from the displayed image should different enough from the sunlight that the light from the displayed image exiting through the film should not be affected.

In addition to the films, the US Air Force Research Laboratory has designed two hoods for the HMD (see Figure 2), which have the potential to prevent the experience of glare. In contrast to the films, the hoods are geometrically designed to shield the HMD from the sunlight. These hoods surround the HMD viewing panel and function similar to the bill on a hat by shielding the light from entering the HMD's viewing panel, where it is reflected off the beam splitter back into the user's eye. As shown in Figure 2, the hood on the left uses a circular design and the hood on the right uses a rectangular design. The reasoning for the two designs is that in order to be successful at shielding the light, the hood must be compatible with the geometry of the user's face. Since facial geometry is unique to each individual, these two designs attempt to conform to a majority of the users.

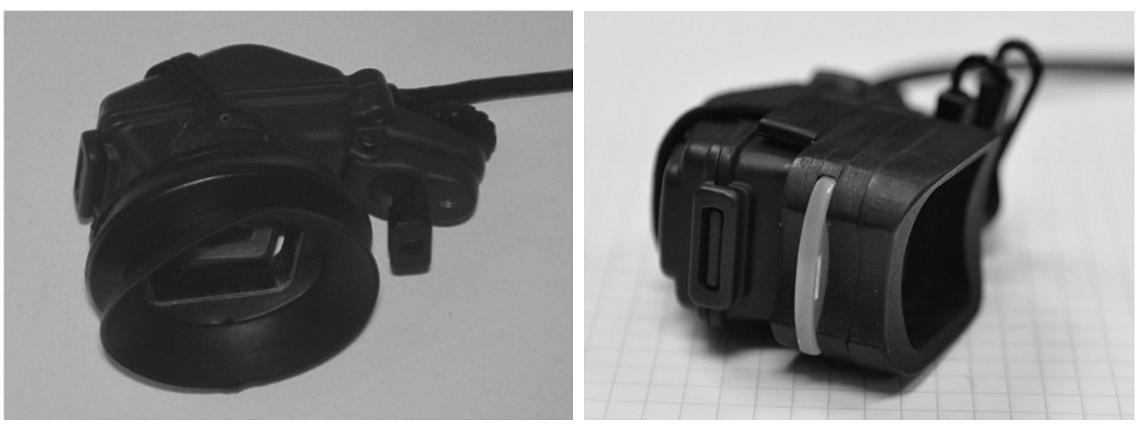

Figure 2. US Air Force Research Laboratory designed HMD hoods 1 (left) and 2 (right) for the HMD

The glare experienced by the operator ultimately affects the contrast ratio of the displayed image[8]. It was found through the use of a liquid-crystal display (LCD) that a reduction in contrast ratio produces a corresponding reduction in the readability of the LCD's displayed image[8]. Additionally, previous research suggests that contrast ratio also has a significant effect on legibility[9]. Under a number of different color combinations, as contrast ratio increases, legibility increases[8]. Furthermore, it was found that contrast ratio also has a significant effect on visual performance[10]. A comparison of different contrast ratios on visual acuity using a pseudoisochromatic chart likewise found that visual acuity increases as the contrast ratio increases[10].

From this previous research, it appears that the problem associated with glare is its effect on the contrast ratio of the displayed image. Since the literature suggests that AR film, microlouver film, and polarizing film all appear to have the potential of reducing the effect of glare on contrast ratio, and since the two HMD hoods are geometrically designed to prevent the effect of glare on contrast ratio by shielding the HMD's viewing panel from the sunlight, a series of experiments were performed to compare the films and hoods as potential solutions to the problem experienced by the operators. The first experiment examined the effectiveness of the different films and HMD hoods at reducing the amount of light being reflected off the viewing panel of the HMD. The second experiment examined screen readability/legibility and the ability to identify targets on a map with the use of the film coverings and HMD hoods under both a glare condition and a no glare condition.

Although each film and hood possess a unique characteristic that allows it to be a candidate for a potential solution to the problem experienced by users, we predict that wearing these anti-glare applications may negatively affect the readability of the display. Thus for optimal results, the Vuzix Tac Eye Lt. would either need to be worn as designed or be redesigned for the preferred wearing position.

2. METHODOLOGY

2.1 Experiment 1 (Objective Measure)

2.1.1 Measures

The independent variable in this experiment (viewing panel treatment) consisted of six levels (AR film covering, microlouver film covering, polarizing film covering, no covering, and the two HMD hoods). The dependent variable (reading from a photometer) was measured in candelas per meter squared (cd/m^2).

2.1.2 Supplies and Setting

The supplies used in this experiment included one Vuzix Tac Eye Lt. HMD, one photometer, one 600-watt studio lamp, a gooseneck clamp, a table, a black tablecloth, the three film coverings, and the two HMD hoods. The experiment took place in a room painted completely black, with dark carpet, and black ceiling tiles (to prevent the reflectance of light off of any other source except the HMD).

2.1.4 Procedure

To begin, the table was covered with the black tablecloth and the gooseneck clamp was attached to the ledge of the table. The HMD was then secured to the other end of the gooseneck clamp, and angled up appropriately. The 600-watt studio lamp was then turned on and positioned (see Figure 3) to create a large bloom of light on the HMD's viewing panel. Each viewing panel treatment was then consecutively applied and three reading were taken with the photometer for each treatment.

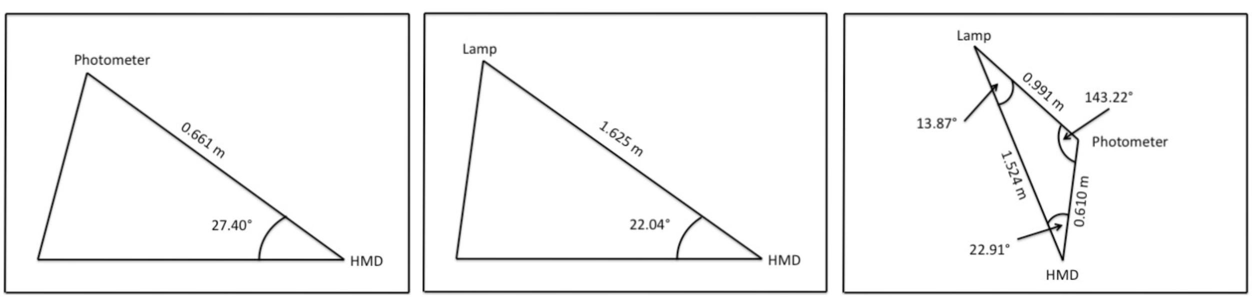

Figure 3. Photometer to HMD set-up (left); Lamp to HMD set-up (center); Top-down view of photometer to HMD to lamp set-up (right).

2.2 Experiment 2 (Subjective Measures)

2.2.1 Participants

A total of ten participants were chosen to participate in the experiment. This group included both men & women, and had an age requirement between 18-30 years of age. Additionally, all participants had normal or corrected-to-normal vision. Participants received monetary compensation for their time.

2.2.2 Measures

The independent variable in this experiment (viewing panel treatment) consisted of six levels (AR film covering, microlouver film covering, polarizing film covering, no covering, and the two HMD hoods), and was examined under two lighting conditions (glare and no glare). As a result, the experiment was conducted with each participant individually as a within-subject design and consisted of twelve tests (one for each treatment under both lighting conditions). The dependent variables (words identified and icons identified) were measured by whether or not the specified color of a word was identified on the screen and the total number of icons correctly identified on a map.

2.2.3 Supplies and Setting

The supplies needed for the experiment included one Vuzix Tac Eye Lt. HMD, one laptop computer containing the Microsoft® PowerPoint™ software (slides with different colored words randomly distributed on the page and slides with maps containing randomly distributed colored icons were used), one 600-watt studio lamp, a gooseneck clamp, a table, a black tablecloth, the three film coverings, and the two HMD hoods. The experiment took place in a room painted completely black, with dark carpet, and black ceiling tiles (to prevent the reflectance of light off of any other source except the HMD). The surrounding environment was relatively quiet with no distracters.

2.2.4 Procedure

Since this experiment had a within-subject design and the independent variable had six levels (AR film, microlouver film, polarizing film, no application, and the two HMD hoods), which were examined under two lighting conditions (glare and no glare), the experiment was conducted with each participant individually and consisted of twelve tests. In addition to the set up in Experiment 1, a chin rest, chair, and laptop computer were added. The chin rest was attached to the table, and the HMD was positioned next to the chin rest. The HMD was then connected to the laptop computer. The first participant was then brought into the room and instructed to sit in the chair at the desk. The following procedures were then performed with each participant.

Before the experiment began, the participant was informed of their task, the actions they were permitted to perform, the amount of time allotted for identification, and an approximation of the amount time required for the experiment. The participant was informed that at no time during the experiment might they use their hand or any other object as a means to shield the projected light from hitting the HMD (during the glare condition). None of the participants wore a hat or head covering that would shield the projected light.

After instruction, the participant was given a color blindness test using a series of pseudoisochromatic plates. If the participant passed the color blindness test, they continued on to a second vision test that was conducted via the HMD (this was performed to insure the participant could read a font size similar to one used in the GIS program). To perform this test, the participant was directed to sit facing the chin rest and to place his/her chin in the chin rest. The participant was then told to adjust the HMD into the direct line of sight (the designed wearing position) of their right eye. Following completion of this positioning, the participant was told to place their hands on the desk and the second vision test began. This vision test consisted of the three colored icons that would be used in the experiment (the colors included red, yellow, and blue), rows of random black letters that decreased in font size from 38 to 6, and a list of five colored words that resemble the words used in the experiment (the colors included red, blue, green, yellow, and orange). If the participant was able to correctly identify the colors of the icons, correctly read the row that was font size 12, and was able to correctly read the colored word (eg. the moderator would prompt the participant to read the "blue-colored word"), then the he/she would continue on to a practice test for the experiment.

The practice test was the same type of test that would be performed for the twelve tests of the experiment, except that no treatment was applied to the viewing panel of the HMD and the test was performed under a no glare, normal room illumination condition. The objective of this test was to acquaint the participant with the tasks to be performed, and to answer any questions he/she may have. Results of this test were not recorded.

Each of the twelve conditions of the experiment was conducted in the same manner. Before each test began, the moderator secured a viewing panel treatment to the HMD (excluding the "no application" condition). The moderator told the participant to position the HMD just above their maxilla/zygomatic bone, angled up towards their eye (as the operators wear it) and to center a set of crosshairs that were displayed on the HMD screen. After correctly positioning the HMD, the participant was told to place their hands on the desk and to not move their head or any other part of the body, unless told to do so by the moderator (see Figure 4). If the test involved the studio lamp (i.e. the “glare” condition), the ceiling lights in the room were turned off and the lamp was turn on. If the test did not require the use of the lamp (i.e. the “no glare” condition), the ceiling lights in the test room remained on for safety (note: the ceiling lights did not create glare on the HMD). Between each test, the crosshairs were once again displayed on the HMD and the moderator received confirmation from the participant that they were still centered.

Figure 4. Experimental setup for the subjective measures under glare (left) and no glare (right) conditions.

For each “glare” test, the moderator positioned the studio lamp until the participant claimed they were experiencing a glare bloom that was centered (as closely as possible) on the crosshairs they were viewing through the HMD. The moderator gave the participant a pen and a paper representation of that same set of crosshairs and prompted them to draw what they were seeing on the paper crosshairs. Additionally, the moderator verified their experience by visually assuring that the reflection of the lamplight off the HMD was indeed projected onto their right eye (when possible).

During each of the twelve tests in the experiment, the participant was presented with five slides containing maps with randomly placed, colored icons and five slides containing five randomly-placed, colored words on a white background (both were presented using Microsoft® PowerPoint™ slides). The maps and the lists of words alternated until the participant completed all ten slides. The computer presented each slide for ten seconds.

During the map task, each participant was told to determine the number of superimposed icons *of a specific color* that they found on the map (the moderator used a randomization technique to determine which icon color the participants should report). For the word recognition task, the moderator asked the participant to identify a word printed in a particular color (again, the color prompt was randomized). To count as a correct response, the participant had to read back the word presented in that color. The words shown in this task were randomly selected from a list of uncommon terms to prevent the participant from guessing the whole word after seeing only a part of it. As part of both tasks, the participant was instructed to remain silent during the ten-second exposure to the stimulus. Once the ten seconds ended, the screen turned black and the moderator asked for the participant’s response.

Once a test was completed, a different viewing panel treatment was applied to the HMD (except the “no application” condition) and the next test proceeded. This process continued until all application and glare conditions were complete.

Additionally, the participants completed the same test with the HMD worn in the proper position, with no anti-glare application and under ceiling lighting conditions as a manipulation check to ensure that performance on this task was not hampered by the HMD itself (“baseline” condition).

3. RESULTS

3.1 Objective Measure

To get an intuitive sense of how bright the glare appeared in this objective test, we measured the brightness of a flat-white reference tile at M=661cd/m^2; by contrast, the uncovered HMD returned a rather large bloom of light at M=4620cd/m^2. The results of this initial study reveal that the microlouver film (M=385cd/m^2) appeared to be the most effective solution for eliminating glare from the HMD, returning 92% less light than the uncovered HMD (refer to Figure 5 for objective measures). The polarizing film (M=1060cd/m^2, 77% less than uncovered HMD) also seemed to be a good candidate for reducing the glare. However, the anti-reflective film (M=900cd/m^2, 33% less than uncovered HMD) had a mediocre performance in this test.

Since the HMD hoods are meant to shade the HMD from the light, rather than scatter it, it was not a surprise that in this test, they returned a similar amount of light as the uncovered HMD (M=4340cd/m^2 and M=5290cd/m^2, for hoods 1 and 2, respectively).

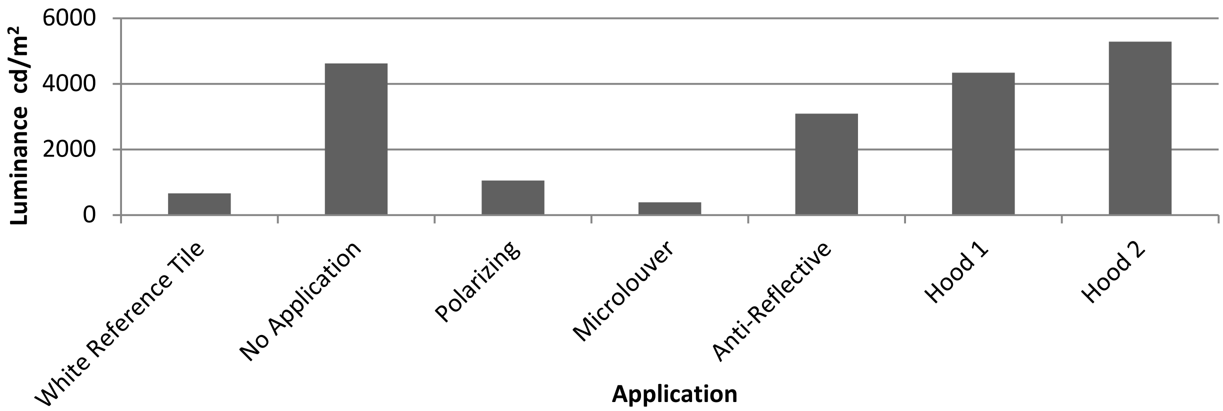

Figure 5. Amount of light reflected off HMD screen for each anti-glare application

3.2 Subjective Measures

3.2.1 Map Reading Task

Analysis by a 5 (application) x 2 (glare condition), repeated-measures ANOVA revealed a main effect for glare, $F(1,9) = 20.013$, $p < .05$, with those in the no glare condition (M=78%, SD=23%) scoring significantly higher than those in the glare condition (M=55%, SD=27%), indicating that performance on this task was negatively affected by the presence of the glare, regardless of the application used to mitigate it (refer to Figure 6 for the map reading task measures). There was also a main effect for application, $F(5,10) = 3.552$, $p < .05$. However, there were no significant interactions between glare and application. A pairwise comparison of this omnibus analysis showed that the only significant difference across applications was between the no application condition (M=80%, SD=21%) and the anti-reflective condition (M=60%, SD=26%), $p<.05$, suggesting the participants' performance on this task was actually hampered by this film.

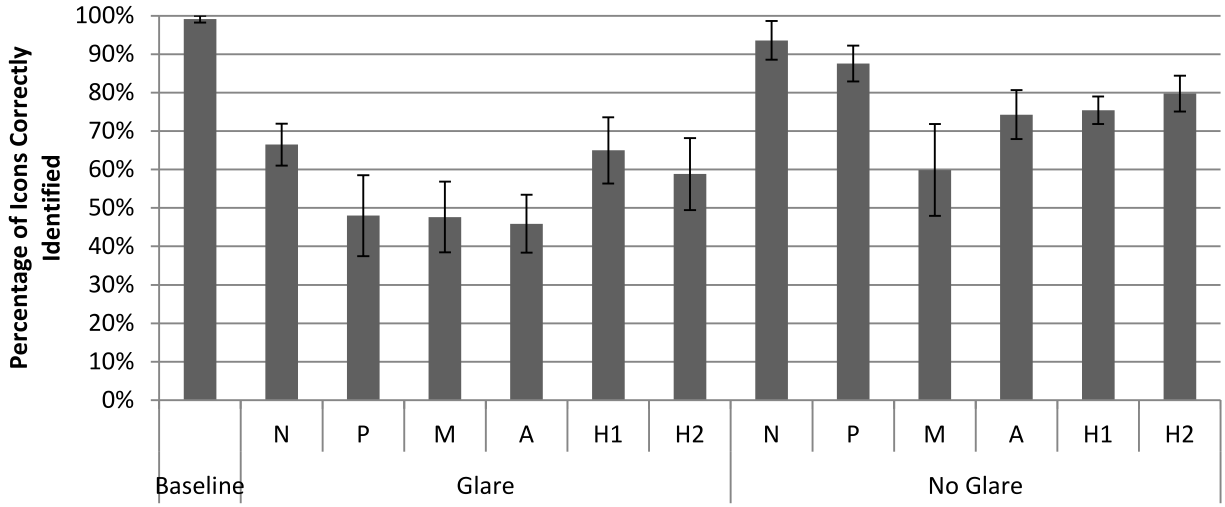

Figure 6. Results of the map reading task (error bars represent 1 SEM).
N = no application; P = polarizing film; M = microlouver film; A = anti-reflective film; H1= hood design 1; H2 = hood design 2

3.2.2 Word Recognition Task

As with the map reading task, a 5 x 2 repeated-measures ANOVA was used to analyze the data from the word recognition task, likewise showing a significant main effect for glare, $F(1,9) = 39.128$, $p<.001$, and for application, $F(5, 9) = 14.648$, $p<.001$ (refer to Figure 7 for the word recognition task measures). The participants once again performed better in the no glare condition (M=55%, SD=34%) than the glare condition (M=26%, SD=28%) and there were significant differences between the application conditions. Again, there were no interaction effects for application x glare. However, when breaking the omnibus analysis into pairwise comparisons, the results indicate that the microlouver (M=14%, SD=17%) and anti-reflective (M=13%, SD=29%) film conditions both performed significantly worse than the no covering condition (M=57%, SD=27%), $p<.02$, and $p<.01$, respectively.

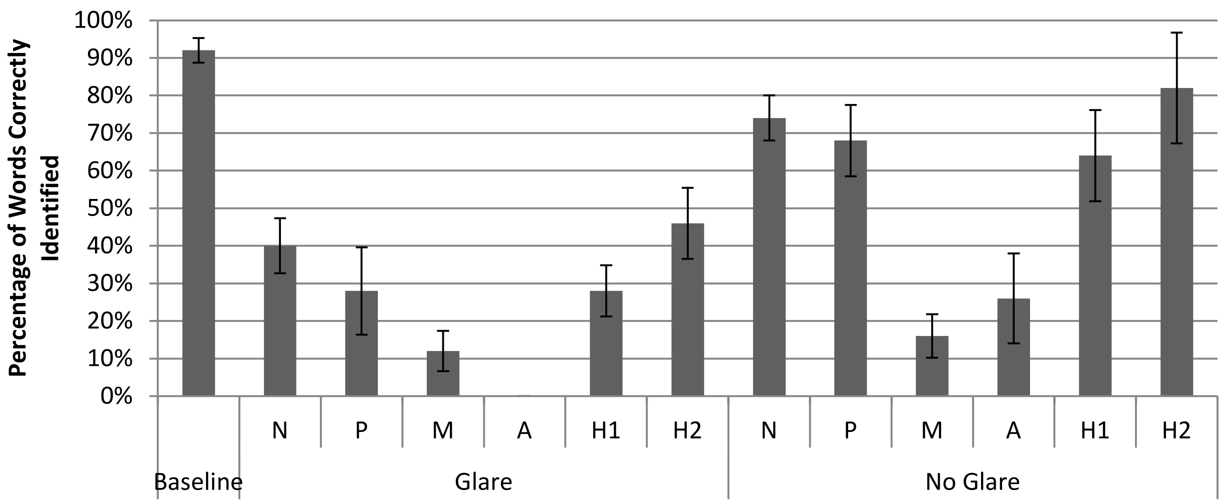

Figure 7. Results of the word recognition task (error bars represent 1 SEM).
N = no application; P = polarizing film; M = microlouver film; A = anti-reflective film; H1= hood design 1; H2 = hood design 2

4. CONCLUSIONS

4.1 Baseline Measurement

The results of our baseline measurement demonstrate that when worn properly, the participants were able to perform both the map reading and word recognition tasks with near perfect accuracy. These data offer convergent validity to the earlier findings of Burnett et al[11], which showed that users should be able to view most information presented on a Tac-Eye LT easily, even when worn on a boom mount (which only slightly degrades the user's FOV). This baseline also suggests that our experimental manipulation is sound and that any effect on the participants' performance was likely the result of the experimental treatments, rather than some artifact of the test setup.

4.2 Effectiveness of the Film Applications

Initially, the data gathered during the objective test revealed that the microlouver film would be the most effective solution for eliminating glare from the HMD. However, the results of this film in the subjective test reveal that it performs significantly worse than the no application condition in both a "glare" and "no glare" condition. This outcome is not surprising and supports the previously mentioned notion that while microlouver film may be sufficient in reflecting away external light, it may also limit the angle at which the light from the displayed image can be viewed[6]. It appears that the angle of the louvers within the film is successfully reflecting away the external light from the HMD's viewing panel, but is also limiting the angle at which the light from the displayed image can be viewed. While microlouver film may be designed to contain louvers angled perfectly, for one instance, to both reflect away external light from the HMD viewing panel and to permit light from the displayed image to be viewed, it is impractical to consider this film as a solution because in a battlefield scenario the sun's position would be changing throughout the day (hence, the angle of the external light would be changing), and the HMD would have to be worn exactly in the same position every time.

The polarizing film performed well in the objective test and also during the no "glare" condition in the subjective test, but performed poorly under the "glare" condition in the subjective test. Based on how well the film eliminated glare during the objective test, it was surprising to see that the film performed so poorly under a glare analysis in the subjective test. Since the film attenuates the wavelength of the external light that penetrates its surface[7], it is believed that during this process the film is producing a 'tinting" effect and thus dimming the light from the displayed image. This 'tinting" effect is believed to be the reason for the disparity in the results. Regardless, since this film did not perform significantly better than the no application condition under both a glare and no glare analysis in the subject test, it will not be considered a solution to the problem.

The results of the anti-reflective film in the objective test reveal that it is the least effective solution for eliminating the glare out of the film applications, and is only slightly better than a no application condition. Additionally, the results of the film in the subjective test reveal that it performs very poorly under the "no glare" condition and performs significantly worse than all the other films under a "glare" condition (with a 0%). Since the film's composition produces a destructive interference of the light within the film[5], it is believed that during this process the film is scattering the light in such a way that it is causing the displayed image to appear blurry. Since this film is commonly used on LCD monitors that are positioned at a relatively farther distance from the eye than the HMD, it is possible that this blurring effect could be function of how much larger the imperfections of the anti-glare film appear with respect to the HMD's viewing surface. Regardless, since this film performed so poorly overall in both tests, it will not be considered as a solution to the problem.

4.3 Effectiveness of the Hood Applications

Although the current set of experiments provided us with an initial opportunity to test how the participants' performance was affected by applying each HMD hood to the display, it was *primarily* designed to evaluate the effectiveness of the different film applications. Since we shined the studio lamp directly on the HMD during the objective measure and the "glare" condition of the subjective measure, the results showed us how each film scattered the light (more specifically, how each film affected the amount of light reflected off the surface of the HMD and how each film affected the readability of the display). However, the real strength of these hoods is that they shield the surface of the HMD from light in the environment, rather than scattering it as the films do. By using the same test paradigm for the HMD hoods, we are essentially testing their effectiveness under a worst-case scenario (ie. what happens if the user is positioned in such a way that allows sunlight to shine through the hood and directly onto an uncovered HMD). Therefore, one should keep this in mind when interpreting the results of both the objective and subjective measures for these hoods.

Nevertheless, it is still useful to conduct these experiments with the hoods since it is possible that the hoods may occlude part of the screen when worn below the eye. By examining how well each hood performed with respect to the “no application” condition, one may be able to see if these hoods might somehow degrade the user’s performance in this manner.

In the first experiment, we recorded the intensity of the glare bloom coming off the surface of the HMD with each hood attached. Despite the fact that the first hood slightly dampened the glare bloom, the second actually amplified the effect a small amount. Even though the entire prototype is made from black plastic, it is possible that the inner surface of this hood was channeling the light somewhat. This suggests that later prototypes of this design may perform better if the inner surface were coated with a flatter black material.

During the second experiment, the hoods did not perform significantly better or worse than the “no application” condition, regardless of the glare condition or whether the subject was performing a map reading task or word recognition task. This suggests that the hoods are not interfering with the readability of the display, as we had feared (if anything, hood 2 performed marginally better than the uncovered HMD on the word recognition task, though this effect was not significant). Although there were no significant pairwise differences between the two hoods, as an overall trend, participants tended to perform better when wearing hood 2 than hood 1.

Since these tests showed that the hoods did not significantly impair the user’s ability to see the display, a hood design may prove to be a good interim solution until we can field an HMD with an integrated anti-glare solution. However, further investigation may be necessary to see if the hood’s glare-shielding properties are worth the extra weight and bulk.

4.4 Opportunities for the Design of Next Generation HMDs & Directions for Future Research

One way we may be able to sort out how well the hoods shield the HMD from glare is to run the subjective measure again. However, this time one could see how well participants performed on each task depending on the position of the studio lamp with respect to the subject’s eye. If the hood manages to shield the display from more of the environmental light across the different lamp positions, then one would have strong empirical data to support a hood solution. On the other hand, perhaps an easier way to evaluate possible hood designs is to conduct some field trials of the prototype to see if the users notice a difference in their mission effectiveness by wearing the hoods on sunny days.

Based on the findings of this study, we discovered that the filters do not solve the glare problem and that the hoods may provide good interim solution. Nevertheless, to completely address this issue, one might lobby for some more permanent modifications for the next increment of HMD design. The current angle of the beam splitter of the Vuzix Tac Eye Lt. was positioned based on the assumption that the HMD would be worn directly in the line of sight of one of the eyes. Since the actual wearing position is different than what was envisioned, one of the potential solutions to the glare problem involves a redesign of the HMD to adjust the angle of the beam splitter based on this preferred wearing position. The figure below (see Figure 8) illustrates this adjustment as proposed by Harry Lee Task, Ph.D. of Task Consulting. The design on the left closely resembles the current design of the HMD, except for a slight adjustment to the angle of the beam splitter. Another option purposed by Task, which also requires a redesign of the HMD, includes the incorporation of a cube-shaped beam splitter (the design the right). This redesign concept not only adjusts the angle of the beam splitter, but also adjusts the positioning of the OLED display and the concave mirror. The adjustments made to the HMD in both redesign concepts will prevent the external light from being reflected directly into the eye.

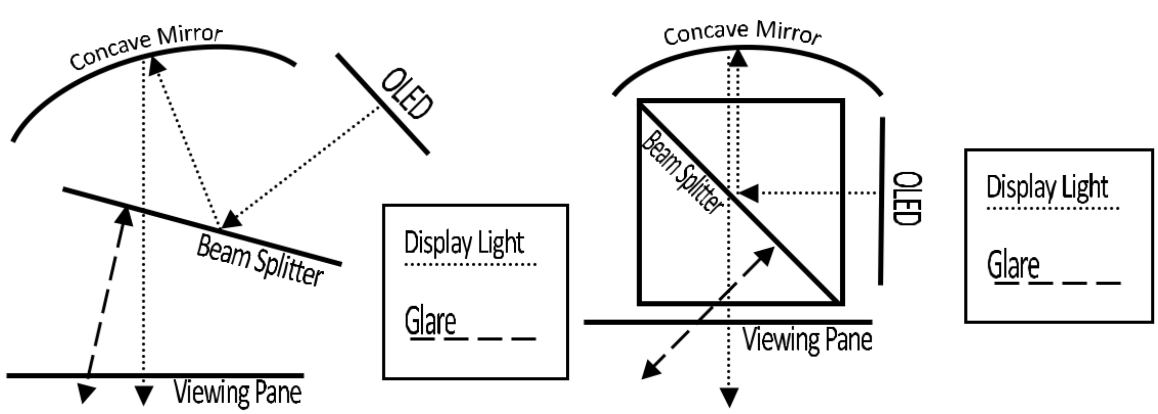

Figure 8. Two possible ways to redesign the position of the beam splitter to reflect glare away from the user's eye

Moreover, if further testing validates the hood design, one may also recommend that an integrated hood solution be included in the next increment of the HMD design cycle.

These insights may influence the direction of future increments in the life cycle of HMD acquisitions for battlefield airmen. However, it is much easier and cheaper to investigate how operators may use particular piece of kit such as HMDs *before* they are produced in large quantities. By uncovering new, unanticipated use-cases early on, designers can include issues like glare reduction as a requirement at a stage when the HMD design is more malleable.

ACKNOWLEDGMENTS

We would like thank Dr. Yan Liu at Wright State University in Dayton, Ohio for her thoughtful discussions and guidance, which helped us in the writing of this paper. Also, we would like to thank Dr. Harry Lee Task, of Task Consulting for his HMD redesign concepts. Finally, we would like to thank those who assisted us in conducting this study: Stephanie Regis, Amanda Hull, Greg Burnett and Jill Ritter of the Air Force Research Laboratory at Wright-Patterson Air Force Base in Dayton, Ohio; and Christopher Edman, Billy Swayne, and Mike Sedillo of Ball Aerospace and Technologies Corporation in Dayton, Ohio.

REFERENCES

[1] Ritter, J.A., Bean, R., Burnett, G., Mieskoski, R., Finomore, V., Militello, L.G., "Tools for Battlefield Airmen: Where we've been and where we're going," Panel Discussion. HFES Annual Meeting, 55 (submitted for review).

[2] Illuminating Engineering Society of North America (IESNA), Lighting Handbook: Reference and Application (9th ed.), New York, NY (2000).

[3] Shi, W., Lockhart, T.E., and Arbab, M., "Tinted Windshields and Its Effects on Aging Driver's Visual Acuity and Glare Response," Safety Science, 46(8), 1223-1233 (2008).

[4] Ludt, R., "Three Types of Glare: Low Vision O&M Assessment and Remediation," RE:view Rehabilitation and Education for Blindness and Visual Impairment, 29(3), 101-113 (1997).

[5] Walheim, S., Schäffer, E., Mlynek, J., and Steiner, U., " Nanophase-Separated Polymer Films as High-Performance Antireflective Coatings," Science, 283, 520-522 (1999).

[6] Dobrowolski, J.A., Sullivan, B.T., and Bajcar, R.C., "Optical Interference, Contrast-Enhanced Electroluminescent Device," Applied Optics, 31(28), 5988-5996 (1992).

[7] Fujikake, H., Takizawa, K., Aida, T., Kikuchi, H., Fujii, T., and Kawakita, M., "Electronically-Controllable Liquid Crystal Polarizing Filter for Eliminating Reflected Light," Optical Review, 5(2), 93-98 (1998).

[8] Chung, H., and Lu, S., "Contrast-Ratio Analysis of Sunlight-Readable Color LCDs for Outdoor Applications," Journal of the Society for Information Display, 11(1), 237-242 (2003).

[9] McLean, M.V., "Brightness Contrast, and Legibility," Human Factors: The Journal of the Human Factors Society, 7(6), 521-526 (1965).

[10] Wang, A., and Chen, M., "Effects of Polarity and Luminance Contrast on Visual Performance and VDT Display Quality," International Journal of Industrial Ergonomics, 25(4), 415-421 (2000).

[11] Burnett, G., Hoover, J., Racine, M., and Sedillo, M., "Human System Integration Considerations For Tactical Head Mounted Displays," Proc. SPIE 7688, 119-129 (2010).