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14. ABSTRACT

Many liquid crystal displays (LCDs) operate by acting as a light valve to selectively block or transmit light emitted from a backlight. Due to the imperfect nature of the LCD light valve, when the LCD pixel is in the "off" state, it is not perfectly opaque, and some small portion of the backlight bleeds through. This imperfect dark state, or black level, is a well-known drawback of LCD displays. In low-light augmented reality helmet mounted display (HMD) applications, this bleed-through can significantly obscure real-world objects viewed through the display. In this work, we investigate the performance impact of a non-zero dark state in simulated low-light formation flight scenarios using a monochrome green HMD. Observer performance was evaluated at several different dark state luminance levels for tasks that require locating or tracking an aircraft with active navigation lights under starlight illumination. Adaptation time between relatively high and low dark state conditions was also characterized. In this paper we focus on the challenges associated with implementing the operational scenario, including calibration of both the simulation and HMD, with discussion of human performance under varying brightness conditions. These methods can be used to accurately calibrate training simulations in which highly realistic representations of low-light see-through HMD operations are a critical requirement for effective training.

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EFFECTS OF HMD BACKLIGHT BLEED-THROUGH IN LOW-LIGHT AUGMENTED REALITY APPLICATIONS

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ABSTRACT

Many liquid crystal displays (LCDs) operate by acting as a light valve to selectively block or transmit light emitted from a backlight. Due to the imperfect nature of the LCD light valve, when the LCD pixel is in the "off" state, it is not perfectly opaque, and some small portion of the backlight bleeds through. This imperfect dark state, or black level, is a well-known drawback of LCD displays. In low-light augmented reality helmet mounted display (HMD) applications, this bleed-through can significantly obscure real-world objects viewed through the display. In this work, we investigate the performance impact of a non-zero dark state in simulated low-light formation flight scenarios using a monochrome green HMD. Observer performance was evaluated at several different dark state luminance levels for tasks that require locating or tracking an aircraft with active navigation lights under starlight illumination. Adaptation time between relatively high and low dark state conditions was also characterized. In this paper we focus on the challenges associated with implementing the operational scenario, including calibration of both the simulation and HMD, with discussion of human performance under varying brightness conditions. These methods can be used to accurately calibrate training simulations in which highly realistic representations of low-light see-through HMD operations are a critical requirement for effective training.

INTRODUCTION

The use of helmet mounted displays (HMDs) for augmented reality or vision enhancement has significantly increased in recent years, with greater application to vehicle operations. However, such displays may not provide enhanced vision or situational awareness in all scenarios, causing performance trade-offs based largely on the display technology. Liquid crystal displays (LCDs) have been used in a variety of HMD designs and generally exhibit backlight bleed-through. While the performance impact of this bleed-through is typically negligible in bright ambient lighting, it may become the dominant visual element under low ambient lighting conditions. In many HMDs it is not possible to reduce the backlight bleed-through; thus, it becomes necessary to train the operator under realistic lighting conditions such that the performance impact becomes well understood.

In this work, we describe the calibration of a simulated low-light augmented reality formation flight task performed using an HMD with simulated backlight bleed-through. The performance impact is subsequently measured in simulated aircraft detection and formation flight tasks, including the transition time between backlight activation and deactivation.

BACKGROUND

Prior to the relatively recent introduction of organic light emitting diode (OLED) displays in HMD applications, LCD light valves had been the most widespread HMD display technology. This has resulted in a wide variety of LCD-based HMDs being fielded over the preceding years that are currently in service and will continue to be in service for many more years. Thus, operators of such systems must be well informed of the effect backlight bleed-through may have on operational performance.

LCDs typically operate by acting as a light valve to selectively block or transmit light emitted from a backlight, typically an LED or, in older displays, a fluorescent light source. Due to the imperfect nature of the LCD light valve, when the LCD pixel is in the "off" state it is not perfectly opaque, and some small portion of the backlight bleeds through the LCD panel and is visible to the user. This imperfect dark state, or black level, is a well-known drawback of LCD displays. This backlight bleed-through is always present, although it is typically only noticeable in very dim (mesopic) ambient conditions. However, in low-light augmented reality HMD applications, this bleed-through can significantly obscure real-world objects viewed through the display, as shown in Figure 1. In low-light

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augmented reality applications, the presence of backlight bleed-through can significantly obscure the view of the real-world objects, thus greatly impacting performance. The brightness of the entire scene is uniformly increased, which effectively lowers the scene contrast. For very low contrast features (e.g., aircraft and ship silhouettes, terrain details, etc.), the addition of even a small amount of backlight bleed-through may render these features either partially or completely unobservable.

Figure 1: Simulated images of aircraft in low ambient lighting conditions without (top) and with (bottom) monochrome green backlight LCD bleed-through. Note the decreased visibility of low contrast scene content.

To adequately prepare operators for this decrement in performance, it becomes necessary for HMD training environments (e.g., flight simulators, etc.) to implement properly controlled scene contrast for applicable training scenarios.

CALIBRATION PROCEDURE

In this work, both an HMD and projection display were carefully calibrated for conducting psychometric evaluations of human performance under various HMD backlight bleed-through conditions. However, the calibration procedures described herein are generalizable to many low-light training scenarios using HMDs.

HMD Calibration

In this work, an SA-62/S HMD (Figure 2) was used to emulate a range of backlight bleed-through levels to replicate the performance of multiple fielded systems. The SA-62/S is a semi-transparent HMD with a 53ºx33º field of view with two 1920x1200 full color OLED displays intended for biocular augmented or mixed reality applications. Because the SA-62/S display technology is OLED, in which the pixels themselves are emissive, there is no backlight bleed-through. The OLED pixels can be driven to true "zero" luminance, allowing a range of non-zero bleed-through levels to be emulated. Note that this work was conducted using the green channel only in an effort to study the performance impact of several fielded monochrome HMDs, although these methods are generalizable to full color calibrations.

Figure 2: SA-62/S HMD.

The SA-62/S permits programmatic control of the HMD brightness via USB communication to allow the drive voltage of the OLED to be reduced to very low levels. This effectively compresses the dynamic range of the display, which allows very precise control of the simulated bleed-through without introducing quantization errors due to the 8-bit video signal. The SA-62/S also includes thermal correction to control OLED luminance drift with operating temperature.

Each eyepiece of the SA-62/S was calibrated using a Minolta CS200 chromameter centered in the HMD exit pupil. Luminance measurements were recorded at video signal increments of 0.05, from 0.05 to 1 (13 to 255) over the 8-bit green channel and fit using a 5th order polynomial, as shown in Figure 3. It is notable that, prior to correction, the left and right eyepieces of the SA-62/S differed substantially in brightness, while exhibiting a luminance ceiling effect at video levels above 0.95.

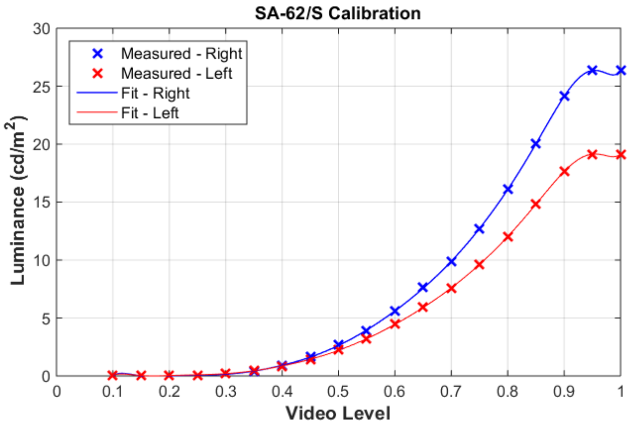

Figure 3: SA-62/S calibration over a compressed brightness range.

The data shown in Figure 3 were used to generate specific video signal levels to hold the simulated bleed-through at precise, equal levels in each eye piece. The bleed-through levels under investigation are all under 2 cd/m^2, using video levels falling between 0.2 and 0.4. This range also allows heads-up display symbology to be displayed at adequate brightness (~15 cd/m^2) relative to the bleed-through.

It should be noted that for this specific OLED display, the thermal correction behaved somewhat erratically at the very low luminance levels under investigation and was therefore disabled for data collection. This necessitated the HMD be fully calibrated prior to each use, which consisted of a 30-minute warm-up period at, or near, the intended luminance level and full characterization with the Minolta CS200.

Display Calibration

In addition to the HMD calibration, which is relatively straightforward, the "out-the-window" display must also be carefully calibrated such that the scene content will exhibit appropriate contrast levels relative to the HMD bleed-through. Although most displays are not capable of achieving this for "daylight" representative luminance levels, the illumination range of interest is quite dim and is easily achievable on most simulator displays. A Christie Matrix StIM digital projector was used in this work.

The simulated operational task under study pertained primarily to formation flight under starlight illumination, in which the aircraft navigation lights require accurate representation. The illumination at the eye-point at various simulated distances was modeled as a point source governed by the inverse square law, based upon the FAA minimum luminous intensity of navigation lights viewed from directly behind an aircraft (20 candelas).

At great simulated distances, intensity as a function of distance can be easily represented by changing the intensity of a single pixel. However, at nearer distances, the maximum intensity of a single pixel is limited by the capabilities of the display system and more pixels are required to achieve the required intensity.

Additional light pixels were added when the previous set of pixels was approximately 30% of maximum intensity. For this work, the pixels were added/filled in the sequence shown in Figure 4 and the intensity of the individual pixels was adjusted to make the intensity integrated over space inversely proportional to the square of the simulated distance.

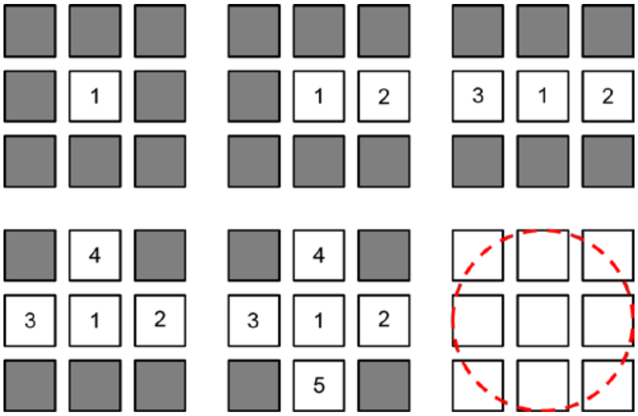

Figure 4: Fill order of light pixels (white) vs. dark pixels (gray). The red dashed line represents the approximate integration area of the Minolta CS200 chromameter over a region of nine pixels.

The integrated intensity of these light points was measured with a Minolta CS200 to verify adherence to the inverse square law. It should be noted that any number of pixels less than 9 would underfill the CS200, which is an integrating detector. Thus, the measured value must be corrected by a "fill factor," which is proportional to the area the light pixel occupies within the integration area of the CS200 (see Figure 4). Any non-zero contribution of the dark pixels must also be subtracted. The resulting inverse-square calibration is shown in Figure 5.

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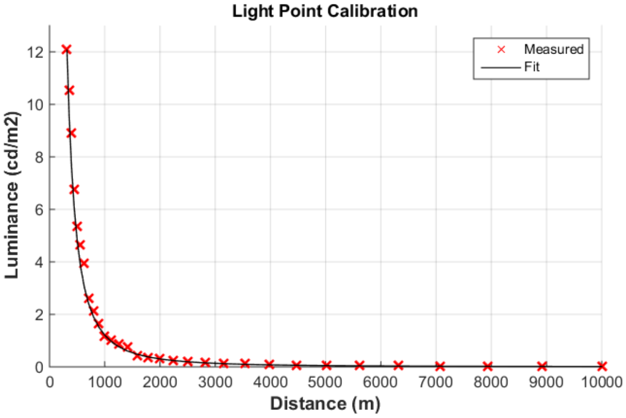

Figure 5: Inverse square law light point calibration of Christie Matrix StIM projector.

The design eye point was located 3.5 m from the StIM projection. At this distance a single pixel subtends 1.11 arcminutes.

SIMULATED OPERATIONAL TASKS

Three psychometric scenarios were designed to assess the impact of backlight bleed-through on operational performance. First, a static detection task was performed under various levels of constant backlight bleed-through, then repeated as the bleed-through was cycled on/off to quantify adaptation time. A formation flight task was also developed to gauge the impact of bleed-through on dynamic tracking.

Each of the simulated operational tasks was implemented in X-Plane. The light point control was implemented using a custom pixel shader written in Visual Studio (C++) using the X-Plane software development kit. The control host and psychometric procedures were written in MATLAB using UDP multicast communication with X-Plane.

Static Detection Task 1

The initial static detection task consisted of navigation lights of a KC-135 fixation target and a stimulus aircraft positioned either to the left or right of the KC-135, as shown in Figure 6. The KC-135 fixation target remained at a fixed brightness level that can be seen through all levels of green glow. The stimulus aircraft is randomly positioned on either the left or the right of the fixation target, and the subject indicates this position as a two-alternative forced choice response. The distance, and thus brightness, to the stimulus aircraft varies in an adaptive manner controlled by the Ψ algorithm (30 trials) such that correct responses generally result in more difficult/dimmer stimuli, while incorrect responses result in brighter stimuli. (Kingdom and Prins, 2010). The result is an individual luminance threshold (cd/m^2) at which the subject is able to make a correct response with 81% probability of success.

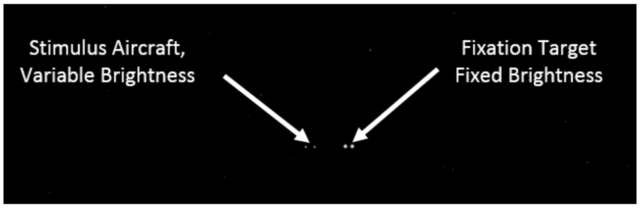

Figure 6: Appearance of the stimulus and fixation target navigation lights.

This experiment was performed on seven participants with good contrast sensitivity for seven levels of green glow spanning 0 to 1.7 cd/m^2, with the resulting luminance threshold plot shown in Figure 7. Each participant achieved a threshold stimulus within the presentation range of a single pixel.

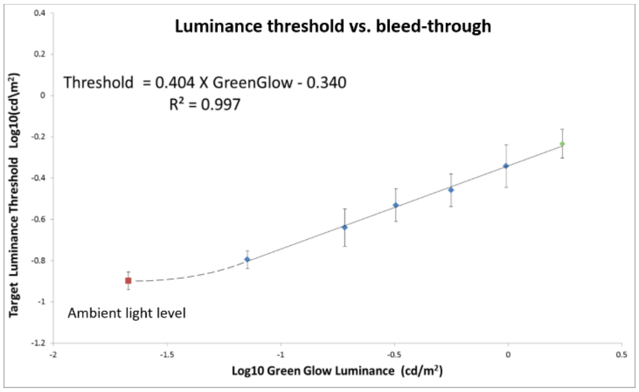

Figure 7: Luminance threshold vs. backlight bleed-through, spanning 0 to 1.7 cd/m^2.

Figure 7 illustrates a characteristic luminance threshold response in which the brighter the HMD display bleed-through, the brighter the target must be to be reliably visible. The slope of 0.4 on the log scale is close to the value one would expect (0.5) if performance was limited by Poisson (i.e., shot) noise of the bleed-through. The threshold Weber contrast ranges from 6 in the absence of bleed-through to approximately 0.3 under the brightest bleed-through.

Static Detection Task 2

The static detection task was repeated to assess adaptation and recovery time as the bleed-through is switched on or off. This simulates the adaptation that an HMD user would encounter when initially donning or removing the HMD in a dim environment. In this scenario, stimuli were repeated at 3-second intervals over a period of 36 seconds in which the bleed-through is activated at the maximum level (1.7 cd/m^2) for 18 seconds, then deactivated (0 cd/m^2) for 18 seconds. Stimuli were specifically timed to occur at the moments of bleed-through activation and deactivation. The results are shown in Figure 8.

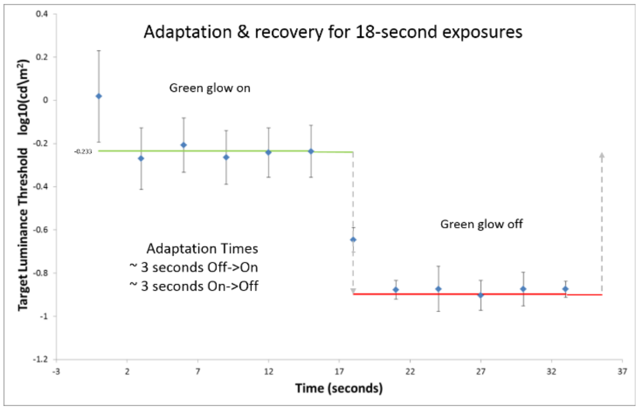

Figure 8: Luminance thresholds for bleed-through adaptation and recovery. Green and red lines represent mean luminance thresholds from static detection task 1 for both the brightest and dimmest bleed-through conditions.

As Figure 8 illustrates, the adaptation and recovery times are both on the order of 3 seconds or less, which is the temporal resolution of the experiment. This is in agreement with previously published literature (Howard et al., 2001).

Dynamic Tracking Task

To assess the impact of backlight bleed-through for dynamic stimuli, a formation flight task was simulated. This task consists of a lead aircraft that follows a pseudo-random sum-of-sines path along the horizontal direction, as shown in Figure 9. The subject is required to follow directly behind the lead aircraft using a joystick with a single degree of freedom (horizontal). Both the instantaneous and mean tracking errors of the subject were recorded for each of seven backlight levels, which each spanned a 1-minute exposure. Note that Figure 9 depicts a daylight scene for illustration purposes only. The experiment was conducted as a night scenario, similar in appearance to Figure 6.

Figure 9: Illustration of pseudo-random sinusoidal path for the dynamic tracking task.

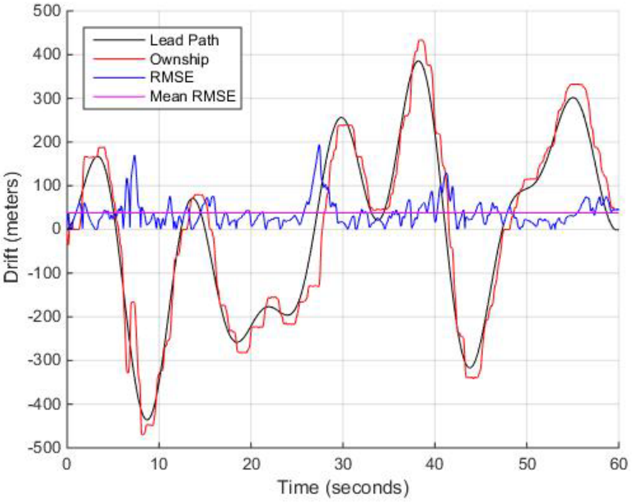

Figure 10: Tracking task data illustrating the pseudo-random lead path (black), the subject's attempt to follow the lead path (red), the instantaneous error magnitude (blue), and the root mean square (RMS) error (magenta) over a 1-minute backlight exposure.

A representative set of formation flight data is presented in Figure 10, which characterizes the baseline performance (i.e., tracking accuracy) of a participant in the absence of backlight bleed-through. Figure 11 illustrates the evolution of the RMS tracking error for a typical subject as bleed-through is increased over seven levels for a constant stimulus value of 0.58 cd/m^2. The target stimulus value was chosen to be the mean stimulus threshold of the seven participants at the brightest bleed-through level (1.7 cd/m^2).

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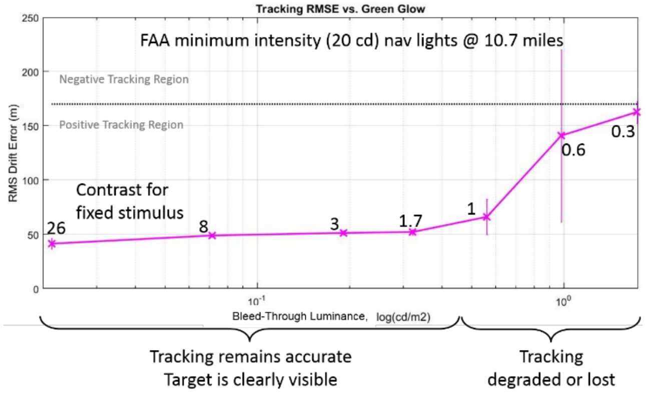

Figure 11: RMS tracking error for seven bleed-through levels and a 0.58-cd/m^2 target stimulus. The Weber contrast of the stimulus at each level is also labeled at each luminance level.

It can be seen that tracking error is minimal for target contrast levels greater than 1, but dramatically increases as the contrast is reduced further (greater bleed-through). Notably, the standard error of the mean increased dramatically near a contrast level of 0.6. It is presumed that this is the region near a subject's individual contrast threshold for this stimulus. For contrast levels greater than 1, the target can be clearly and consistently identified and tracked through the backlight bleed-through. For contrast levels below 0.3, the target is clearly and consistently *not* identified or tracked. The wide standard error near a contrast of 0.6 suggests that *sometimes* the target is seen, and other times it is not, resulting in intermittent tracking.

DISCUSSION

These experiments illustrate that backlight bleed-through can have a significant and quantifiable impact on operational task performance. Furthermore, these data suggest that individual contrast sensitivity may play some role in task performance under these conditions. Therefore, to support effective training, the degree of backlight bleed-through and display content should be properly calibrated to simulate realistic performance decrements. Notably, it is the overall scene contrast, rather than absolute luminance levels, which must be calibrated in this manner. Considerable research and development have been devoted to properly simulating night vision goggle characteristics (e.g., halos, auto-gain, visual illusions, etc.) to support training. Similar research and development may be required to ensure that aircrew are familiar with the unique capabilities, and idiosyncrasies, of HMDs as their use becomes more widespread. However, it must be emphasized that the psychometric experiments performed here simulated a specific task (point source localization) using subjects with normal contrast sensitivity. Although the concepts here are generalizable to other scenarios, particular data are not. For example, the ability to correctly identify and track a high-contrast point source is not the same as tracking a low-contrast extended target. This would be representative, for example, of the difference between flying formation at night using navigation lights versus viewing an aircraft carrier silhouette against a dark sea. In each case, the levels of backlight bleed-through that result in unacceptable performance would be necessarily different and may be further complicated by individual differences in contrast sensitivity.

CONCLUSION

The importance of display contrast calibration has been demonstrated via psychometric experimentation, and specific levels of HMD backlight bleed-through have been shown to correlate with performance decrements. A detailed method of calibrating an HMD display system to yield a given contrast level for low-light augmented reality applications was also presented and discussed.

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