Exploring the Limitations of Environment Lighting on Optical See-Through Head-Mounted Displays

Austin Erickson*
University of Central Florida
Orlando, Florida
ericksona@knights.ucf.edu

Kangsoo Kim
University of Central Florida
Orlando, Florida
kangsoo.kim@ucf.edu

Gerd Bruder
University of Central Florida
Orlando, Florida
bruder@ucf.edu

Gregory F. Welch
University of Central Florida
Orlando, Florida
welch@ucf.edu

ABSTRACT

Due to the *additive light model* employed by most optical see-through head-mounted displays (OST-HMDs), they provide the best augmented reality (AR) views in dark environments, where the added AR light does not have to compete against existing real-world lighting. AR imagery displayed on such devices loses a significant amount of contrast in well-lit environments such as outdoors in direct sunlight. To compensate for this, OST-HMDs often use a tinted visor to reduce the amount of environment light that reaches the user's eyes, which in turn results in a loss of contrast in the user's physical environment. While these effects are well known and grounded in existing literature, formal measurements of the illuminance and contrast of modern OST-HMDs are currently missing. In this paper, we provide illuminance measurements for both the Microsoft HoloLens 1 and its successor the HoloLens 2 under varying environment lighting conditions ranging from 0 to 20,000 lux. We evaluate how environment lighting impacts the user by calculating contrast ratios between rendered black (transparent) and white imagery displayed under these conditions, and evaluate how the intensity of environment lighting is impacted by donning and using the HMD. Our results indicate the further need for refinement in the design of future OST-HMDs to optimize contrast in environments with illuminance values greater than or equal to those found in indoor working environments.

CCS CONCEPTS

• **Hardware → Displays and imagers**; • **Computing methodologies → Mixed / augmented reality**; **Perception**.

KEYWORDS

Augmented Reality, Optical See-Through Head-Mounted Displays, Illuminance, Contrast, Environment Lighting, Visual Perception

ACM Reference Format:
Austin Erickson, Kangsoo Kim, Gerd Bruder, and Gregory F. Welch. 2020. Exploring the Limitations of Environment Lighting on Optical See-Through Head-Mounted Displays. In *Symposium on Spatial User Interaction (SUI '20), October 31-November 1, 2020, Virtual Event, Canada.* ACM, New York, NY, USA, 8 pages. https://doi.org/10.1145/3385959.3418445

1 INTRODUCTION

Optical see-through head-mounted displays (OST-HMDs) provide the means to present augmented reality (AR) visual information to users, e.g., by projecting light onto a surface which is then reflected into the user's eyes. This is known as an *additive light model* because the display adds light on top of the existing light reaching the user from their physical environment [5–7]. A known problem with this type of display method is that when the user is in particularly bright environments, such as outdoors during the day, then the virtual imagery on the display tends to lose contrast in relation to the environment [1]. In bright environments, such as outside in direct sunlight, the virtual imagery may not even be visible to the user at all (see Figure 1).

Because of this inherent challenge of OST-HMDs, the majority of such displays incorporate a visor with a neutral density filter into their design, which slightly dims the physical environment and often results in increased contrast between the environment and AR imagery for users. While such a visor helps increase contrast in a variety of use cases, it can be problematic in dimly lit environments because the overall contrast of light and dark objects in the physical environment is reduced. This means that users may not be able to distinguish between low contrast physical objects while wearing the HMD, in a manner similar to wearing sunglasses at night.

While these problems are well known by users of OST-HMDs, AR is becoming more important to a wide array of domains and applications [16, 29], and it is important to understand exactly when these reduced contrast scenarios occur and what type of physical objects and virtual imagery are affected by them. To our best knowledge, these effects have not been quantified on current generation HMDs, so in this paper, we present a study in which illuminance measurements are made under varying environment

---

[*] Corresponding author.

SUI '20, October 31-November 1, 2020, Virtual Event, Canada

ACM ISBN 978-1-4503-7943-4/20/10…$15.00
https://doi.org/10.1145/3385959.3418445

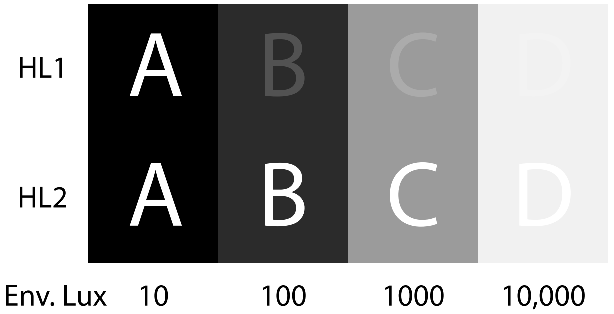


Figure 1: This figure illustrates four different contrast levels in varying environment illuminance conditions on the HoloLens 1 and 2 (HL1 and HL2). Due to variations in the reader's circumstances (e.g., environmental light, display parameters, and/or print quality) the appearance of this figure will differ from the appearance in the OST-HMD, but it provides an indication of how difficult it would be to discern virtual content on these devices under different lighting conditions. The background colors for the row labeled HL2 were calculated by plugging in the contrast ratios obtained from the study in table 2 and fixed foreground RGB values of 255 to equation 1. The foreground color for the HL1 row were similarly calculated by inserting the fixed contrast ratio as well as the background RGB value calculated in the HL2 row into the same equation.

lighting conditions using both the Microsoft HoloLens 1 and its successor, the HoloLens 2.

Our results indicate that while the HoloLens 2 outperforms the HoloLens 1 in terms of illuminance and contrast, both HMDs achieve their best results in low-light environments, achieve sub-optimal results in the range of lighting conditions in which most indoor work occurs (between 100 and 1000 lux), and are practically unusable in outdoor environments with lighting levels greater than 10,000 lux.

These results indicate the need for further refinement in the design of OST-HMDs to achieve better contrast ratios in common lighting conditions. They also highlight the importance of measuring environment illuminance in AR research in order to understand what exactly the users of the OST-HMD will be experiencing. Unfortunately contrast issues will likely take several iterations of consumer OST-HMDs to resolve, however in the meantime, this paper's main contribution is its ability to serve as a convenient reference for future research involving these HMDs where the contrast ratio of the virtual content is a concern. Such future works are benefited by being able to quickly refer to the tables and figures presented here in order to estimate the contrast ratios they will obtain for their specific virtual content given their environment lighting conditions.

The remainder of this paper is structured as follows: Section 2 presents related work on reduced-contrast AR scenarios and provides an overview of human visual perception in terms of contrast sensitivity. Section 3 outlines the methods and materials used in collecting the illuminance measurements on the HoloLens 1 and 2. Section 4 presents the results of our measurements in the form of illuminance values, contrast ratios, and contrast sensitivity functions. Section 5 provides a discussion of the results and their relation to established literature in the field. Section 6 concludes the paper.

2 BACKGROUND

In this section, we provide a brief overview of human visual perception in terms of contrast sensitivity and we present a summary of related work that involved reduced-contrast AR scenarios. For more in depth reading on the human visual system and physiology of the eye from the ground up, we recommend referring to the online text by Stangor and Walinga [28].

2.1 Human Visual Contrast Sensitivity

In the field of human visual perception, the ability of a person to distinguish a physical stimulus is typically based on the size and contrast of the stimulus compared to the environment. Distinguishing a visual stimulus based on its size is typically referred to as *visual acuity* and well-covered in the existing literature [4, 12, 18].

Contrast sensitivity is typically defined as a person's ability to distinguish a visual stimulus based on the differences in luminance between it and its environment [26, 27]. One way to calculate the contrast of basic visual stimuli is Michelson's contrast, which is characterized by the following equation, where I_{min} is the luminance of the stimulus (which is typically black) and I_{max} is the luminance of the background (which is typically white):

$$\textbf{Michelson Contrast: } \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

While this contrast can be measured using specialized light meters, there are multiple psychophysical tests to measure users' sensitivity to such contrasts. An example is the sine wave grating test, in which sine wave grating patterns are presented to the subject at varying contrast levels, spatial frequencies, and direction, where subjects are tasked to identify the direction of the gratings (typically either vertical or horizontal). Contrast level is quantified as a ratio between the color of the sine pattern and the background behind it, and is varied by displaying the sine wave pattern to the user in different shades of grey, where darker shades offer more contrast than lighter shades. Spatial frequency can be thought of as size, and is quantified in cycles per degree of visual angle. It is similarly varied by increasing the amount of repeated sine wave patterns found in the set area that is presented to the subject.

When a person's contrast sensitivity levels and spatial frequency levels are plotted on the axes of a figure in logarithmic scale, then the resulting graph of the person's contrast sensitivity function typically takes on the form of an inverted letter 'U' (see Figure 2). This shape is expected, as the stimulus is more difficult to identify when contrast is low, as there is little difference in color between the sine grating and the background, or when the spatial frequency is high, as there is little separation between repeated wave patterns on the stimulus.

Visual stimulus that falls outside a person's contrast sensitivity function can be dealt with in two different manners, either by increasing the spatial frequency (e.g., its size), or by increasing the contrast. However on OST-HMDs, screen space is valuable due to the limited field of view on most devices. Because of this, increasing

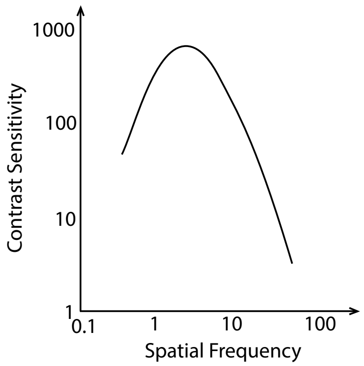


Figure 2: Illustration of a contrast sensitivity function, where contrast sensitivity is the reciprocal of the lowest contrast stimulus a person is able to distinguish.

spatial frequency in reduced contrast situations only works so long as the image fits within the field of view of the device. With this upper bound on spatial frequency, any additional change to make imagery distinguishable to the user must come from adjusting either the contrast between the foreground and background colors of the virtual imagery or the contrast between the foreground color of the virtual imagery with the user's physical environment.

2.2 AR Reduced-Contrast Scenarios

Contrast sensitivity has been examined frequently in existing literature, where it has been found that the simple act of donning an OST-HMD has the effect of reduced contrast on the user's physical environment, and changes to the manner in which users' perceive color [21, 22]. There are several factors that can cause a reduction in contrast with OST-HMDs, e.g., environmental factors like dynamic or saturated lighting conditions and see-through backgrounds. Tinted visors attached to see-through displays are often used as a practical solution to increase the contrast between virtual imagery by reducing the illuminance levels of the environment lighting. However, the tinting inevitably reduces the visibility of the real scenes in low lighting environments and prevents accurate color perception.

To address perception issues in such reduced contrast scenarios, researchers conducted studies that investigate the perception thresholds and design guidelines for augmented content in OST displays. For example, Harding et al. [9] presented an HMD simulation model that could simulate different see-through background images with overlaid white-color symbology, and showed that the perceptual quality of the symbology was greatly influenced by the complexity of the backgrounds, which was characterized by the standard deviation of small patches of luminance in the images. Beyond the white-color symbology, Harding et al. [10] further studied luminance and color contrast requirements while discussing the color choice for more effective symbology in OST-HMDs.

Gabbard et al. [5] also pointed out the challenge in presenting virtual content, specifically text information, in outdoor AR environments due to dynamic lighting conditions and uncontrollable backgrounds in the environment. They found that the text legibility is highly affected by the text drawing style, the see-though background, and their interaction. Merenda et al. [23] considered in-car HUD interfaces and conducted a study that investigates the user's color identification performance in different color-blending circumstances caused by the mixture in the colors of background and augmented text/symbolic content. They found that participants generally chose brighter colors as compared to the original source color of the content, but certain colors, e.g., blue, green, and yellow, were more accurately identified.

There is also continuous effort on developing display techniques and devices for color contrast and reproduction. Itoh et al. [13, 14] presented a series of display methods to improve the visual quality of virtual content in OST-HMDs. For example, they proposed a color calibration method that pre-processes the input image to match the user-perceived color on the display to the original image color [13] and introduced a new light attenuation approach that forms images by spatially subtracting colors instead of the traditional additive color approach [14]. Hincapié-Ramos et al. [11] addressed a similar problem by investigating methods of altering the appearance of text to preserve the intended color, and introduced methods of preserving the intended color while also increasing contrast. Donval et al. [2] proposed a smart filter for OST-HMDs that could adaptively change the filter transmission according to the background illumination. Leykin and Tuceryan [20] examined predictions of the legibility of text by using machine learning based classifiers, however their work did not take into account the how text annotations appear more transparent as environment lighting conditions increase.

Several other methods have been established for improving the contrast of virtual text specifically, and these largely fall into methods that either alter the appearance of the text or area surrounding it, or methods that reposition the text. Among these, Gabbard et al. [8] and Kim et al. [17] found that for OST-HMDs, the user experience is typically improved by utilizing bright colored text over dark colored backgrounds, which is the opposite of what users tend to prefer when using other display mediums such as virtual reality HMDs [3], where an interaction effect between the text appearance and virtual lighting occurs such that user perform better with light colored font in dark virtual environments and better with dark colored font in bright virtual environments.

When users were tasked with manually placing annotations, Jia et al. [15] found that users preferred text labels over uniform surfaces, and tended to place annotations over the sky. They further established a method which employs image analysis to identify such preferred locations automatically for annotations. Orlosky et al. [25] developed a similar automatic annotation system, however their procedure involves prioritizing locations which are darker and uniform, so that annotations are less affected by environment illuminance.

3 METHODS

This section describes the material and methods we used to perform our illuminance measurements, which are reported below in Section 4.

3.1 Material

In this experiment, we measured *illuminance* values. Illuminance is a photometric measure of the intensity of light which is falling upon, or illuminating, a given surface as perceived by the human eye, and typically uses units of lux, or lumen per square meter (lm/m^2). Illuminance differs from the photometric measure of luminance, which is the amount of light traveling through or reflecting off of a given surface dependent on angle, and has units of candela per square meter (cd/m^2), or lumen per steridian square meter ($lm/(sr \cdot m^2)$). Because it is a photometric measure, illuminance measures the perceived brightness of a surface, as seen by a human eye, by weighing the incoming wavelengths of light using a luminosity function which is based on the visual sensitivity of the human eye. This is different from the similar radiometric measure, irradiance, which measures the optical power incident on a surface across a specific range of unweighted wavelengths of light.

We performed illuminance measurements on the HoloLens 1 and 2, which were chosen due to their widespread usage. The HoloLens 1 was released in 2016 and features a diagonal field of view (FOV) of 34 degrees, and a resolution of 1268×720 pixels per eye, while the HoloLens 2 was released in 2019, and features a diagonal FOV of 52 degrees and a resolution of 2048×1080 pixels per eye. All measurements taken with the HMDs powered on were done so with the brightness control settings of each device was turned to 100%. Smaller percentages of display brightness were not tested, since we are primarily concerned with the maximum contrast able to be achieved under each tested light condition. Additionally, assuming the brightness settings affect the display luminance in a linear manner, estimates of illuminance values at smaller percentages of display brightness should be easily calculable as ratios between the measurements taken at 100% screen brightness and the measurements taken with the display powered off.

In order to make the illuminance measurements, we used an Urceri MT-912 light meter, which is capable of making measurements in lux and footcandles. This meter has an accuracy of ±3% of the reading value with an additional ±8 digits on the least significant digit, and is capable of making measurements between one and 200,000 lux, as reported on the Urceri website[1]. A limitation of this particular instrument is that not capable of measuring small illuminance values between zero and one lux, however the HoloLens 1 and 2 are unlikely to be used under such dim light conditions due to the devices' inability to track and map the user's environment without visual features to assist it. For this reason, we decided to proceed with the Urceri MT-912.

We aimed for illuminance measurements in the widest controlled range of environment lighting possible, with the intention of providing measurements that simulate a user in a pitch dark environment as well as bright outdoor conditions. As such, we utilized an array of two dimmable Amzcool XCD01 10,000 lux light therapy lamps to provide a controlled light source for all measurements. These specific lights were chosen due to their high maximum illuminance values and their inclusion of a built in dimmer, which allowed for testing across a wide range of illuminance values comparable to those found in common indoor and outdoor environments.

We positioned these lights immediately adjacent to one another, and positioned the HMDs centered to the lights so that the left eye optics were roughly centered in front of the left light and vice versa. We also slightly inclined the front of the HMD so that the waveguides were parallel to the surface of the two lights.

The Unity game engine was used to present virtual imagery on each HMD. For the HoloLens 1, the imagery was streamed over a local network via the holographic remoting mode and accompanying app on the device. For the HoloLens 2, the same Unity application was deployed to the device in order to prevent the device from presenting a warning message pertaining to its inability to track the environment in reduced lighting conditions. We utilized a plane 3D object presented perpendicular to the user's forward direction, which was rendered using either black RGB pixel values of (0,0,0) or white RGB pixel values of (255,255,255) depending on which condition was being measured at the time. The plane object made use of a standard unlit surface shader, which ensured that the appearance of the plane was not impacted by virtual lighting and was consistent at each pixel position, and was scaled large enough to take up the entire field of view of the display.

3.2 Procedure

The illuminance measurements were made under the following conditions:

- **Environment Lighting:** The dimmer on the environment light sources and the distance between the HMD waveguide and the surface of the lights was varied to achieve illuminance values of 20,000, 10,000, 1,000, 100, 10, and 0 lux.
- **OST-HMD:** The HMD was varied between the Microsoft HoloLens 1 and the HoloLens 2
- **Display Mode:** The display mode was varied to include direct measurements of the lighting without the HMD, measurements on each device while powered off, measurements on each device while powered on and rendering black (transparent), as well as powered on and rendering white.

For each target environment lighting condition, the light therapy lights were dimmed and positioned appropriately from the HMD to achieve the target illuminance value. From this point, 15 sequential measurements were made for each of the following four conditions:

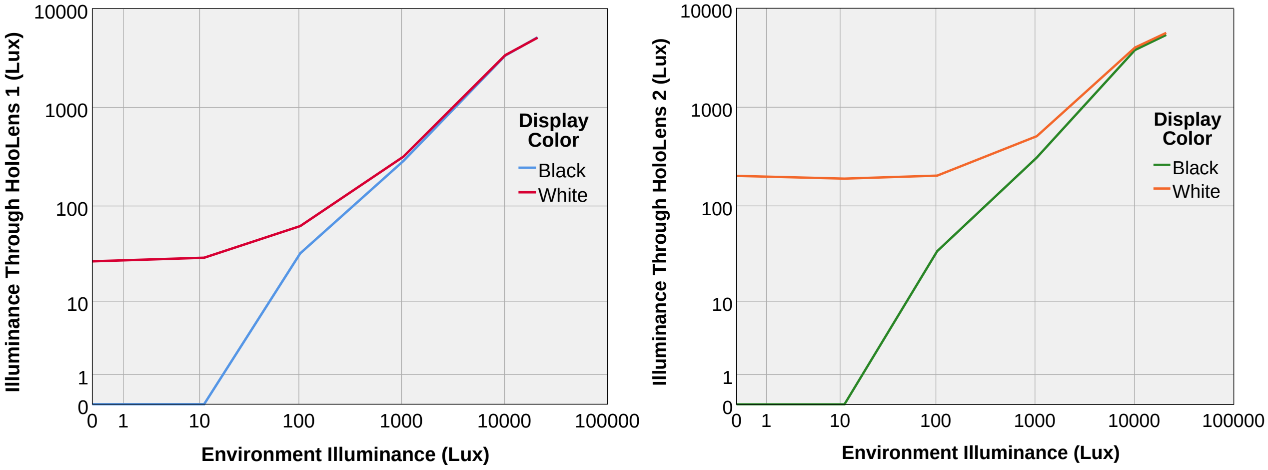
- Without the HMD (measuring the environment lighting directly; not through the visor),
- With the HMD powered off,
- With the HMD rendering *black* (at full display brightness),
- With the HMD rendering *white* (at full display brightness).

The meter was held parallel to the waveguide of the device and directly faced the light fixtures in a position similar to where the user's left eye would be if wearing the HMD. Once each of these sets of 15 measurements were made, the environment lighting was changed to the next target illuminance and the process was repeated.

It is possible that non-uniformity of color due to the optical components of the HMD may cause sequential illuminance measurements to be different due to slight changes in the position and angle of of the measurement device [19]. For this reason, our procedure entails taking 15 sequential measurements from the user's eye position in the HMD to mitigate the effects of such fluctuations.

---

[1] https://www.urceri.com/mt-912-light-meter.html



(a) HoloLens 1

(b) HoloLens 2

Figure 3: Depiction of graphs of the illuminance values measured on the (a) HoloLens 1 and (b) HoloLens 2. The area between the two lines represents the contrast. The axes are presented on a logarithmic scale.

Table 1: This table depicts the average and standard deviation of the illuminance measurements made on the HoloLens 1 and 2 in lux. Values of '<1' are indicated next to measures from the light meter in which only the value 0 was obtained. These measures lay somewhere between 0 and 1 but were not bright enough to be measured with the available equipment.

Environment Illuminance		**HoloLens**	**Display Off**		**Display On: Black**		**Display On: White**	
M	*SD*		*M*	*SD*	*M*	*SD*	*M*	*SD*
20900	325.14	HL 1	4855.73	96.18	5126.47	104.16	5076.73	54.10
		HL 2	5427.53	156.01	5378.60	89.66	5638.8	75.98
10138.07	227.73	HL 1	3418.47	39.03	3342.27	96.67	3378.47	55.06
		HL 2	3806.00	91.96	3785.20	64.92	4007.93	88.23
1043.75	30.82	HL 1	285.22	10.93	287.43	3.19	317.77	7.82
		HL 2	311.41	2.03	309.88	6.98	509.85	7.17
103.11	1.96	HL 1	32.17	1.00	32.54	0.78	62.28	4.04
		HL 2	33.38	1.23	34.27	1.00	203.17	12.63
11.16	1.04	HL 1	<1	0	<1	0	29.28	1.29
		HL 2	<1	0	<1	0	189.43	12.80
<1	0	HL 1	<1	0	<1	0	26.84	2.45
		HL 2	<1	0	<1	0	201.97	14.23

4 RESULTS

4.1 Illuminance

Figure 3 shows the plots of the illuminance values for the HoloLens 1 and HoloLens 2. These plots show the difference in illuminance measurements between the device rendering black (transparent) and rendering white (at the full brightness setting of the HMD). For each of these plots, the area between the lines can be thought of as the level of contrast, which is greatest at environment illuminance levels less than 10 lux, and reduces as the environment illuminance increases.

Table 1 depicts the mean (*M*) and standard deviation (*SD*) of these measurements, broken down by *Environment Lighting*, *OST-HMD*, and *Display Mode*. These measurements show readings of <1 lux in several places when the environment illuminance values are <1 lux and 11.16 lux, and there are several reasons for this. One is because there is ambient light emitted from the HMD when the display is on but rendering black, but this ambient light is not enough to be measured by our light meter. Additionally, the tint of the HMD visor reduces the measured illuminance to be less than 1 lux in several cases, which again is not able to be measured by our light meter. Finally, in the <1 lux environment illuminance condition, values of <1 are written because the testing environment was not pitch black and the ambient illuminance falls somewhere in the range between 0 and 1 lux. Environment lighting with <1 lux is usually observed at night without artificial light sources.

In comparing between display conditions, we can see that the environment illuminance is considerably reduced when viewed

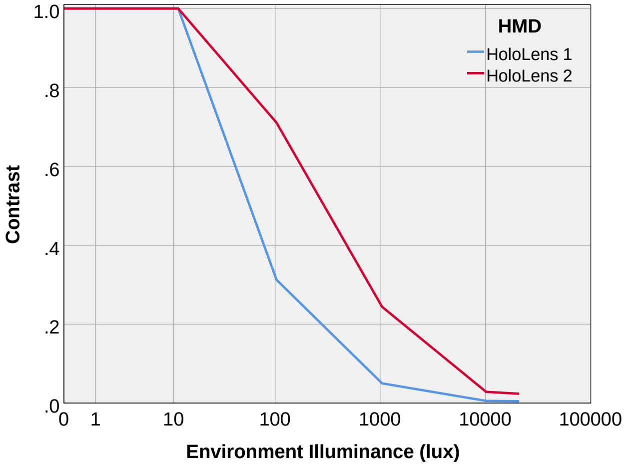


Figure 4: Depiction of the contrast ratios in relation to the environment illuminance levels for each HMD. The x-axis is presented on a logarithmic scale.

through the visor of either of the HMDs. For the HoloLens 1, the amount of environment light of <1, 10, 100, 1,000, 10,000, 20,000 lux was reduced by ~100%, ~100%, 31%, 27%, 34%, 23%, respectively. For the HoloLens 2, the environment light was reduced by ~100%, ~100%, 32%, 29%, 38%, 26%, respectively.

When comparing between the conditions in which the display rendered black (transparent) to the conditions in which the display rendered white, we see an increase between 29 and 37 lux for the HoloLens 1, and an increase between 189 and 261 lux for the HoloLens 2.

The standard deviations in the measurements also increased considerably with the increase in environment illuminance levels. This is somewhat to be expected, as at higher levels of environment illuminance, small deviations in the angle or position of the light meter will have larger impacts on the illuminance measures.

4.2 Contrast Ratios

Using the average luminance values that were found in the above section, contrast ratios were calculated using Equation 1 and the illuminance measurements that were made with the device powered on and rendering black (transparent) and rendering white. In this manner, I_{max} was the illuminance that was the greater of the two measures, and I_{min} was the lesser of the two. While it was expected that the illuminance measurements made with the device rendering white would always be higher than the measurements made with the device rendering black, due to higher deviation in the measurements obtained at high levels of environment illuminance, this was not always the case. The averages and standard deviations of these contrast ratios are presented below in Table 2, and Figure 4 shows the plot of contrast ratios versus the environment illuminance levels for each device.

In general, the contrast ratios from the HoloLens 2 are higher than those from the HoloLens 1, with the ratio decreasing below 3% on the HoloLens 2 and below 0.5% on the HoloLens 1 in the brightest environment illuminance condition.

An illustration of these contrast levels is provided in Figure 1, where visual comparisons can be made between the two HMDs as well as between lighting conditions. It is important to note that this figure is an approximation of the contrast levels users would experience when looking through the HMD, as there is not a concrete method of translating environment illuminance values to pixel values on the reader's display due to individual differences in display parameters between readers.

Table 2: Contrast ratios calculated for the HoloLens 1 and 2 under varying environment lighting conditions. Values of '~1' are used to indicate values in which the lower illuminance measurement was too small to be measured by our equipment, resulting in a contrast ratio of 1.

Environment Light (lux)	HoloLens 1		HoloLens 2	
	M	*SD*	*M*	*SD*
20,900	0.00480	0.0115	0.0236	0.0106
10,138.07	0.00552	0.0187	0.0285	0.0139
1,043.75	0.0500	0.0160	0.244	0.0138
103.11	0.312	0.0367	0.711	0.0173
11.16	~1	0	~1	0
<1	~1	0	~1	0

5 DISCUSSION

The illuminance data we collected demonstrates how big of a factor environment lighting plays on the contrast of the AR imagery. In this section, we compare and discuss the effectiveness of the two HMDs at presenting imagery to a user under varying environment lighting conditions.

5.1 Dim Lighting

Figure 4 demonstrates that both the HoloLens 1 and 2 have reasonable levels of contrast in relatively dim environments where the ambient illuminance is 100 lux or less, such as office hallways. Illuminance levels in this range are recommended for areas in which visual tasks are seldom performed [2] For both HMDs, the best contrast ratio (near 1) is achieved in the darkest of environment lighting conditions, at illuminance values of less than 10 lux. This is partially because the tinted visor of the devices reduced the incoming light to be less than 1 lux from the user's point of view, as shown in the last several rows of Table 1.

While this environment provides the best contrast ratios for observing the virtual imagery presented on the HMD, it also means that the user experiences a loss of contrast when wearing the HMD and attempting to observe their physical environment due to the tinted visor. This means that users would likely have difficulty navigating their physical environment and performing physical tasks in these low light conditions while wearing the HMD.

Under these conditions, the device is also not capable of mapping the environment using its on-board sensors due to the lack of visual features to use in its tracking algorithm, which results in imagery freezing, disappearing, or temporarily becoming user fixed

---

[2] https://www.engineeringtoolbox.com/light-level-rooms-d_708.html

instead of world fixed until conditions improve. On the HoloLens 2 specifically, the operating system will by default interrupt the current running application to display a warning message stating it is unable to track the user's environment, and this message will only disappear after lighting conditions improve. While this behavior can be slightly modified by developers and researchers to specify an image to display when tracking is lost (which is how we displayed our black/white imagery in such lighting conditions), the behavior cannot be disabled. Because of this, it is unlikely that users would often actively use either of the OST-HMDs under these lighting conditions where optimal contrast ratios are achieved.

5.2 Mid Range Lighting

As the environment lighting levels increased to 100 lux, the performance of the HoloLens 1 dropped considerably and achieved contrast ratios of 30%, while the HoloLens 2 achieved contrast ratios of around 70%. These conditions are comparable to a "very dark day" for outdoor environments, and fall below the European Lighting Standard EN 12464 recommended illuminance levels for performing indoor office work which are recommended to be between 500 and 1000 lux [3]. When lighting conditions increased to 1000 lux, the HoloLens 1 achieved a contrast ratio of 5% while the HoloLens 2 achieved around 25%.

These two lighting levels cover the majority of indoor use cases that users may experience while working with OST-HMDs, from dim indoor conditions to brightly lit work environments, and it is interesting to note the spread in contrast ratios achieved on the HMDs (5–30% on the HoloLens 1, and 25–75% on the HoloLens 2). These ranges are sub-optimal and imply that users could benefit from additional light filters on the HMDs, perhaps similar to the methods proposed by Mori et al. [24] in which liquid crystals of variable opacity are used, although the costs of such filters would have to be considered, such as the decrease in contrast of the physical environment and decreased ability of potential collaborators to see the users' faces (which may have impacts in collaborative AR tasks).

5.3 Bright Outdoor Lighting

For both HMDs, the measured contrast was quite low for environment lighting conditions of 10,000 lux or greater. Under these conditions, the HoloLens 1 achieved a contrast ratio of less than 1% and the HoloLens 2 achieved between 2 and 3%. These lighting levels are typically not achieved in indoor environments, and are equivalent to outdoor lighting conditions in full daylight or direct sunlight [3].

With contrast ratios so low, it is unlikely that users would be able to accurately distinguish virtual imagery presented on the HMD, which has been documented in several of the related works described in Section 2. In order to remedy this, virtual imagery would either have to be presented at large scales, which is difficult due to the limited field of view of the devices, or contrast would have to be increased such as by augmenting the device with additional neutral density filters to reduce the amount of environment light reaching the user's eyes.

In future work, with further measurements, it would be useful to model expected illuminance levels from the user's point of view, taking into consideration the light filtering that occurs as light passes through the visor of the HMD. In this manner, one could predict the optimal neutral density filter to attach to the HMD for the given environment lighting condition and desired contrast ratio.

6 CONCLUSION

In this paper we investigated how environment lighting conditions impact the contrast of virtual imagery displayed to the user of an OST-HMD. Our results indicate that there is room for improvement in the design of OST-HMDs, in that they tend to lose a considerable amount of contrast in bright indoor lighting conditions, and tend to lose nearly all contrast when taken into outdoor environments where illuminance levels are greater than 10,000 lux.

We hope that the results presented above will be valuable to future research as a convenient reference for estimating the expected contrast ratios seen by users of the HoloLens 1 and 2, given a particular environment illuminance value. Since the values calculated here are based on measurements in which the display is rendering all white or all black, the contrast ratios we presented are the maximum which can be expected for a particular environment illuminance level. As such, virtual content displayed in colors other than white will likely achieve lower contrast ratios. Future research should take this into consideration when using the above tables and figures to estimate the expected contrast ratios their users will experience under their particular lighting conditions.

In future work, we plan to expand this research by investigating a larger group of modern OST-HMDs. We also plan to take additional illuminance measurements with the device rendering primary and secondary colors, so that contrast ratios can be more accurately estimated for colored UIs and a given environment illuminance value. We further plan to complement the light measurements in this paper with a human subject study to correlate the different contrasts in indoor and outdoor AR with perceptual effects such as visual acuity and legibility of AR annotations. The current COVID-19 pandemic has so far has prevented us from pursuing this research.

ACKNOWLEDGMENTS

This material includes work supported in part by the National Science Foundation under Grant Number 1564065 (Dr. Ephraim P. Glinert, IIS) and Grant Number 1800961 (Dr. Tonya Smith-Jackson, IIS), the Office of Naval Research under Grant Number N00014-17-1-2927 (Dr. Peter Squire, Code 34), and the AdventHealth Endowed Chair in Healthcare Simulation (Prof. Welch). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the supporting institutions. We would also like to thank our friends in Dr. Shin-Tson Wu's research group at UCF's college of optics and photonics for their help in understanding the optics behind OST HMDs, as well as Dr. Michael P. Browne at SA Photonics for his ongoing support and guidance.

REFERENCES

[1] R. Azuma. 1999. The challenge of making augmented reality work outdoors. *Mixed reality: Merging real and virtual worlds* (1999), 379–390.

---

[3] https://www.engineeringtoolbox.com/light-level-rooms-d_708.html

[2] A. Donval, N. Gross, E. Partouche, I. Dotan, O. Lipman, and M. Oron. 2014. Smart filters: operational HMD even at bright sunlight conditions. *Display Technologies and Applications for Defense, Security, and Avionics VIII; and Head- and Helmet-Mounted Displays XIX* 9086 (2014), 90860T.

[3] A. Erickson, K. Kim, G. Bruder, and G. F. Welch. 2020. Effects of Dark Mode Graphics on Visual Acuity and Fatigue with Virtual Reality Head-Mounted Displays. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Atlanta, 434–442.

[4] F. Ferris, A. Kassoff, G. Bresnick, and I. Bailey. 1982. New Visual Acuity Charts for Clinical Research. *American Journal of Ophthalmology* 94, 1 (1982), 91 – 96.

[5] J. Gabbard, J. E. Swan, and D. Hix. 2006. The Effects of Text Drawing Styles, Background Textures, and Natural Lighting on Text Legibility in Outdoor Augmented Reality. *Presence: Teleoperators and Virtual Environments* 15, 1 (2006), 16–32.

[6] J. Gabbard, J. E. Swan, D. Hix, S.-J. Kim, and G. Fitch. 2007. Active Text Drawing Styles for Outdoor Augmented Reality: A User-Based Study and Design Implications. In *Proceedings of IEEE Virtual Reality*. IEEE, Charlotte, 35–42.

[7] J. Gabbard, J. E. Swan, and A. Zarger. 2013. Color blending in outdoor optical see-through AR: The effect of real-world backgrounds on user interface color. In *Proceedings of IEEE Virtual Reality*. IEEE, Orlando, 157–158.

[8] J. L. Gabbard, J. E. Swan, J. Zedlitz, and W. W. Winchester. 2010. More than meets the eye: An engineering study to empirically examine the blending of real and virtual color spaces. In *2010 IEEE Virtual Reality Conference (VR)*. IEEE, Waltham, 79–86.

[9] T. Harding, J. Martin, and C. Rash. 2005. Using a helmet-mounted display computer simulation model to evaluate the luminance requirements for symbology. *Helmet- and Head-Mounted Displays X: Technologies and Applications* 5800 (2005), 159–168.

[10] T. Harding, C. Rash, M. Lattimore, J. Statz, and J. Martin. 2016. Perceptual issues for color helmet-mounted displays: luminance and color contrast requirements. In *Degraded Visual Environments: Enhanced, Synthetic, and External Vision Solutions*, Vol. 9839. SPIE, Baltimore, 98390E.

[11] J. Hincapié-Ramos, L. Ivanchuk, S. K. Sridharan, and P. P. Irani. 2015. SmartColor: Real-Time Color and Contrast Correction for Optical See-Through Head-Mounted Displays. *IEEE Transactions on Visualization and Computer Graphics* 21, 12 (2015), 1336–1348.

[12] J. Holladay. 2004. Visual acuity measurements. *Journal of Cataract & Refractive Surgery* 30, 2 (2004), 287–290.

[13] Y. Itoh, M. Dzitsiuk, T. Amano, and G. Klinker. 2015. Semi-Parametric Color Reproduction Method for Optical See-Through Head-Mounted Displays. *IEEE Transactions on Visualization and Computer Graphics* 21, 11 (2015), 1269–1278.

[14] Y. Itoh, T. Langlotz, D. Iwai, K. Kiyokawa, and T. Amano. 2019. Light Attenuation Display: Subtractive See-Through Near-Eye Display via Spatial Color Filtering. *IEEE Transactions on Visualization and Computer Graphics* 25, 5 (2019), 1951–1960.

[15] J. Jia, Y. Zhang, X. Wu, and W. Guo. 2018. Image-Based Label Placement for Augmented Reality Browsers. In *2018 IEEE 4th International Conference on Computer and Communications (ICCC)* (2018-12). IEEE, San Francisco, 1654–1659.

[16] K. Kim, M. Billinghurst, G. Bruder, H. B. Duh, and G. F. Welch. 2018. Revisiting Trends in Augmented Reality Research: A Review of the 2nd Decade of ISMAR (2008–2017). *IEEE Transactions on Visualization and Computer Graphics* 24, 11 (2018), 2947–2962.

[17] K. Kim, A. Erickson, A. Lambert, G. Bruder, and G. Welch. 2019. Effects of Dark Mode on Visual Fatigue and Acuity in Optical See-Through Head-Mounted Displays. In *Symposium on Spatial User Interaction* (New Orleans, LA, USA) *(SUI '19)*. Association for Computing Machinery, New York, NY, USA, Article 9, 9 pages.

[18] C. Kniestedt and R. L. Stamper. 2003. Visual acuity and its measurement. *Ophthalmology Clinics of North America* 16, 2 (2003), 155–170.

[19] Y.H. Lee, T. Zhan, and S.T. Wu. 2019. Prospects and challenges in augmented reality displays. *Virtual Real. Intell. Hardw.* 1, 1 (2019), 10–20.

[20] A. Leykin and M. Tuceryan. 2004. Automatic determination of text readability over textured backgrounds for augmented reality systems. In *Third IEEE and ACM International Symposium on Mixed and Augmented Reality* (2004-11). IEEE, Arlington, 224–230.

[21] M. Livingston, J. Barrow, and C. Sibley. 2009. Quantification of Contrast Sensitivity and Color Perception using Head-worn Augmented Reality Displays. In *Proceedings of IEEE Virtual Reality Conference*. IEEE, Lafayette, 115–122.

[22] M. Livingston, J. Gabbard, J. Swan, C. Sibley, and J. Barrow. 2013. Basic Perception in Head-Worn Augmented Reality Displays. In *Human Factors in Augmented Reality Environments*. Springer New York, New York, 35–65.

[23] C. Merenda, M. Smith, J. Gabbard, G. Burnett, and D. Large. 2016. Effects of real-world backgrounds on user interface color naming and matching in automotive AR HUDs. In *Proceedings of IEEE VR Workshop on Perceptual and Cognitive Issues in AR*. IEEE, Greenville, 1–6.

[24] S. Mori, S. Ikeda, A. Plopski, and C. Sandor. 2018. BrightView: Increasing Perceived Brightness of Optical See-Through Head-Mounted Displays Through Unnoticeable Incident Light Reduction. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Reutlinger, 251–258.

[25] J. Orlosky, K. Kiyokawa, and H. Takemura. 2014. Managing mobile text in head mounted displays: studies on visual preference and text placement. *ACM SIGMOBILE Mobile Computing and Communications Review* 18, 2 (2014), 20–31. Publisher: ACM New York, NY, USA.

[26] C. Owsley. 2003. Contrast sensitivity. *Ophthalmology Clinics of North America* 16, 2 (2003), 171–177.

[27] D. Pelli and P. Bex. 2013. Measuring contrast sensitivity. *Vision Research* 90 (2013), 10–14.

[28] C. Stangor and J. Walinga. 2014. 5.2 Seeing. In *Introduction to Psychology - 1st Canadian Edition*. BCcampus. https://opentextbc.ca/introductiontopsychology/chapter/4-2-seeing/

[29] G. Welch, G. Bruder, P. Squire, and R. Schubert. 2019. *Anticipating Widespread Augmented Reality: Insights from the 2018 AR Visioning Workshop*. Technical Report. University of Central Florida and Office of Naval Research.