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The effect of an ambient contrast of AR (Augmented Reality) images on brightness perception

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Abstract

In an ideal AR device, only the AR object image should appear in the real environment. However, certain AR devices, such as those using a half mirror, also present the AR background surrounding the AR object due to the transmittance of the half mirror. This might be perceived as a two-dimensional display image overlapping onto the real environment. In this scenario, the perception of brightness might differ from cases where only an AR object is superimposed on the real-world background. To explore the brightness perception of AR images presented by AR glasses with half mirrors, we conducted two psychophysics experiments. In Experiment 1, using a single pair of AR glasses, we observed the brightness perception of AR images under various correlated color temperatures (CCTs) for exterior lighting. Participants perceived the AR image to be brighter than the reference image with the same luminance. The CCT of the exterior lighting had no significant effect. In Experiment 2, we investigated the effect of the AR background on the brightness perception of AR images using two pairs of AR glasses with different transmittances (35% vs. 70%). Participants perceived AR images to be brighter than the reference when using glasses with lower transmittance. These results suggest the interaction effect between the image contrast and the ambient contrast on brightness perception in AR glasses with half mirrors.

Introduction

When images are presented through optical see-through (OST) devices, such as transparent or AR glasses, in ambient conditions, both the light from the images on the OST devices and the light from the real-world background enter the viewers' eyes. Most studies on the brightness perception of Augmented Reality (AR) images assume that only AR object images are superimposed on the real-world background (Figure 1-(a)) [1-4]. These studies conduct experiments to investigate the contrast effect between the AR object in the AR images and the real-world background.

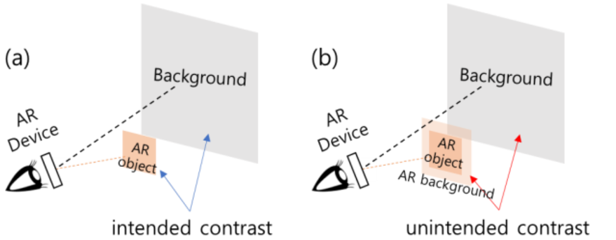

Figure 1. *(a) An intended contrast between an AR object and a background (the real envrionment), (b) an unintended contrast between an AR background and the background (the real environment).*

However, depending on the type of optical system configuration in AR devices, unintended contrasts can arise. This occurs due to the transmittance ratio of a half mirror used in the AR devices. For instance, certain AR glasses like Epson AR glasses use a half-mirror to display AR images, resulting in the appearance of an AR background between the AR object and the real environment. Figure 1-(b) illustrates the unintended contrast between the AR background and the real-world background.

In an ideal AR device, only the AR object image should appear on the real-world background. However, in some actual devices, such as those employing a half mirror, the AR background is also present around the AR object. This might create the perception of a 2D display image overlapping with the real-world background. Consequently, two contrasts can emerge between the AR images and the real-world background: first, the image contrast within the AR image between the AR object and the AR background; second, the contrast ratio between the AR background due to the transmittance of the AR glasses and the ambient real-world background (Figure 2). This contrast can be referred to as "the ambient contrast in the AR background," representing the contrast between the AR background and the real-world background (exterior lighting). When a half mirror with low transmittance is used for the AR glass, the ambient contrast increases, making it challenging for participants to perceive the real-world background, while the AR images can stand out from the background. Conversely, if the AR glass uses a half-mirror with high transmittance, the ambient contrast decreases, making it easier for viewers to see the real-world background, but causing the AR image to blend with the light of the real-world background.

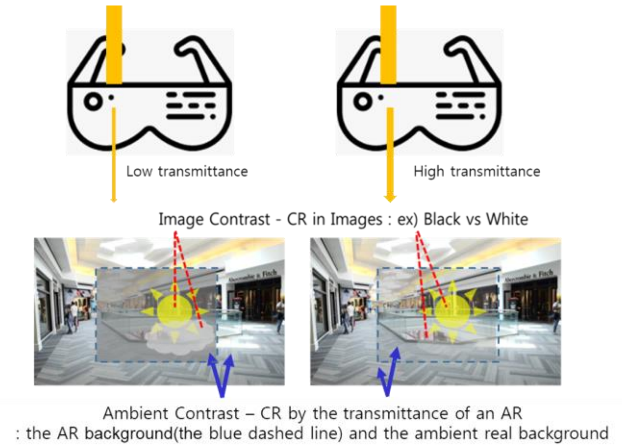

Figure 2. *The examples of two different contrasts on the AR images depending on the transmittance of a half mirror used in the AR glass.*

To investigate the brightness perception of AR images and explore the effect of the ambient contrast from the AR background, we conducted two psychophysics experiments. In Experiment 1, we observed the brightness of AR images using a single pair of AR glasses under various correlated color temperatures (CCTs) of the real-world background. In Experiment 2, utilizing two pairs of AR glasses with different transmittances (35% vs. 70%), we compared the brightness of the AR images. The results of the second experiment will elucidate the impact of the ambient contrast from the AR background on the brightness perception of AR images.

Experiment 1: Perception of AR image brightness in the ambient conditions

Method

To quantify the brightness of the images presented in AR glasses, participants were asked to directly compare the brightness of these images to those displayed on a flat conventional LCD monitor (VIZIO 65-inch LCD display; maximum full white luminance: 1000 cd/m²). The AR glasses presented white AR images as reference stimuli, while the conventional monitor displayed white images as test stimuli. Participants were tasked with adjusting the luminance of the test stimulus on the conventional monitor to match the brightness of the reference stimulus, which was the white AR image. Luminance adjustments were made using the up and down arrow keys on the keyboard.

To ensure a direct comparison of brightness between the AR images and the test stimulus, an experimental environment was developed (Figure 3). First, to quantify the brightness of the AR image in cd/m², it was recommended that the projected AR image have a uniform image plane. This was essential because non-uniformity in the image plane of the AR image superimposed on the real-world background could impact participants' strategies for evaluating brightness [5]. To maintain uniformity, a gray paper uniform surface reflector was placed in front of the lighting booth's surface where the AR images were projected. Second, considering that the difference in three-dimensional depth between the AR image seen through AR glasses and the test image displayed on a flat conventional monitor could influence brightness perception, the conventional monitor was set at the same depth plane as the projection of the AR images. Furthermore, to minimize differences in image size and shape between the AR stimulus and the test stimulus on the conventional monitor, participants were allowed to adjust their viewing distance from the gray reflector to ensure images appeared the same size.

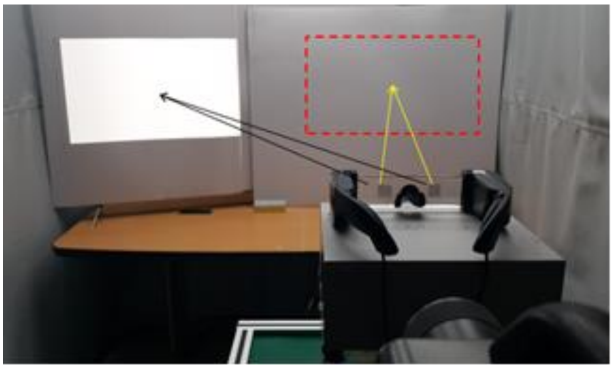

Figure 3. *The experimental setup in EXP 1*

Participants were instructed to gaze at the AR image from the front. They observed an AR image superimposed on the gray reflector projected through the AR device's half-mirror (indicated by the red dashed rectangle in Figure 3). To compare the brightness between the AR image overlaid on the gray reflector and the test images displayed on the conventional monitor, participants were directed to look toward the conventional monitor, placed adjacent to the gray reflector. To avoid the area of the half-mirror, they had to view the test image through the remaining area of the AR device next to the half-mirror's region. Prior to the main experiment, a training session was conducted to ensure participants were comfortable with the task, as it required minimal head movement. The AR glasses used in Experiment 1 were Epson AR glasses (model: BT-100). After participants completed the brightness comparison task, the luminance of the AR images on the gray reflector through the AR glass's half-mirror was measured using a spectrometer (Figure 4-a), both in the dark condition and under ambient conditions. The luminance of the AR images in the dark condition excluded external lighting. Conversely, the luminance of the AR images in the ambient condition included it, which we termed "the total luminance entering the users' eyes." The luminance of the test images on the conventional monitor was also measured through the remaining area of an AR glass (Figure 3 and Figure 4-b), which participants perceived to be equally bright as the AR images. Every effort was made to measure stimulus luminance under conditions as close as possible to those in which participants conducted the brightness comparison task.

Figure 4. *BT 100 and the protocol overview in the exp 1.*

The AR stimuli consisted of full white images with five different gray values viewed through an AR glass. The method of magnitude was employed for the brightness comparison task. Participants concurrently compared an AR image superimposed on the gray reflector (indicated by the red dashed rectangle in Figure 3) through the AR glass with the test stimulus displayed on the conventional monitor (the white rectangle image positioned adjacent to the red dashed rectangle in Figure 3). They adjusted the luminance of the test image on the conventional monitor to match the brightness of the AR image. To mitigate order effects, the test stimulus on the conventional monitor was randomly selected from three stimuli brighter and three stimuli darker than the AR stimulus. The order of the five AR images was randomized, with each AR stimulus presented three times consecutively. Thus, 18 participant responses corresponded to a single AR image. Participants provided a total of 90 responses (5 AR images × 6 test images as starting points × 3 repetitions).

There were two independent variables in this experiment. The This experiment had two independent variables. The first independent variable was the illuminance levels of ambient conditions (3 levels: 750 lx, 1,500 lx, and 3,000 lx). To accurately represent real-world conditions, three indoor environment levels were considered based on a prior study on AR image perception [6]. The second independent variable was the correlated color temperature (CCT) of the ambient conditions (exterior lighting). Three levels (3,000K, 7,300K, and 10,000K) were selected to examine the impact of CCTs on brightness perception.

Participants completed experiments at all illuminance levels in ambient conditions on the same day, taking approximately 90 minutes. The three CCT levels in ambient conditions were conducted on separate days to minimize participant fatigue, and the order of CCTs was randomized for each participant.

The experimental result

Eleven participants took part in the brightness perception experiment of AR images under the ambient condition with a CCT of 3000K. Additionally, twelve subjects participated in the experiment under CCT conditions of 7300K and 10000K. Extreme data points were excluded from analysis (criterion: standard deviation exceeding 3 sigma) to account for potential differences in brightness perception strategies among participants.

Figure 5 illustrates the results across all ambient conditions. The x-axis is measured in units of total luminance entering participants' eyes, which includes the luminance of the AR images in ambient conditions, considering the influence of ambient lighting that passed through the AR glass's half-mirror (Figure 4-a). Notably, participants chose a higher luminance for the white patch images displayed on the conventional monitor compared to the total luminance entering their eyes through the AR device. In essence, participants selected a brighter white patch on the conventional monitor to achieve the same perceived brightness as the AR image in ambient conditions. However, the effect of CCTs did not yield a significant difference.

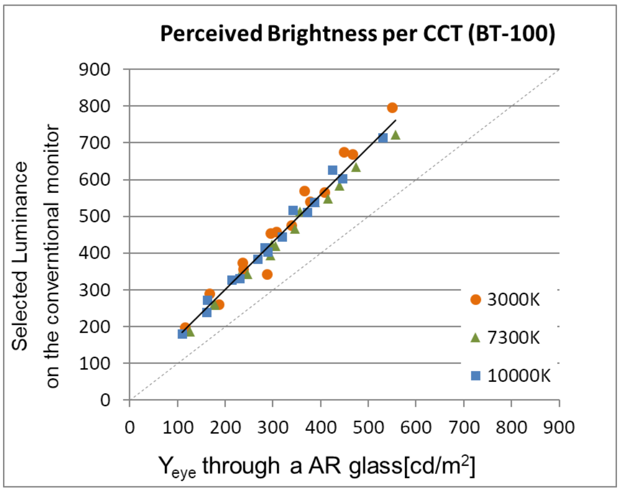

Figure 5. *The result of brightness comparison between the AR images using BT-100 and the white patches on the conventional monitor*

The outcomes indicate that differences in ambient illuminance levels do not significantly impact the results. We propose the following linear relationship equation (1) for brightness perception of AR images:

$$Y_{eye} = Y_{AR} + Y_{lighting} \cdot T_{AR\_M}$$

$$Y_{perceived} = \alpha \cdot Y_{eye} + \beta \quad (1)$$

Where:

Y_{eye} represents the total luminance entering the eyes of a user wearing an AR glass in the ambient conditions, Y_{AR} is the luminance of an AR image in the dark. $Y_{lighting}$ denotes the luminance of the ambient lighting, T_{AR_M} signifies the transmittance ratio of a half-mirror in an AR glass, and $Y_{perceived}$ corresponds to the luminance of a white patch on the flat conventional monitor, as perceived by participants to have the same brightness as the AR image. Through linear regression analysis using Minitab, the value of α was determined to be 1.3 and the value of β was calculated as 38.3 (r2 = 77.27, $p < 0.001$).

This outcome underscores that AR images under ambient conditions are perceived as brighter than 2D images with the same luminance displayed on a conventional monitor. This observation aligns with findings from a prior study indicating that AR users can be influenced by the background brightness [7]. This phenomenon is akin to the transparent effect observed in transparent OLED displays [8], where users perceive AR images as transparent entities.

Experiment 2: Perception of AR image brightness by the ambient contrast

Method

Experiment 2 aimed to investigate the impact of ambient contrast. We defined "ambient contrast" as the contrast ratio between the AR background, determined by the transmittance of the AR half-mirror, and the ambient illuminance (exterior lighting) (as shown in Figure 1). For this investigation, we employed two types of AR glasses: Epson's BT-100 and BT-300 (depicted in Figure 6). The transmittance of the half mirror in the BT-100 was roughly double that of the BT-300 (BT-100: 70%, BT-300: 35%).

Figure 6. *Two AR glasses used in Exp 2 (left: BT-100, right: BT-300).*

In this experiment, the CCT of the ambient condition was kept constant at 4500K, as the CCT effect of the ambient condition did not yield significant results in Experiment 1. Two levels of illuminance were chosen to reflect indoor conditions (750 lx and 3,000 lx). Although the luminances of the AR images with three different gray levels remained consistent across both AR devices, the total luminances entering participants' eyes under each ambient condition varied based on the device due to the differing transmittance of the half mirror. Consequently, we measured the AR images accordingly. The experimental protocol closely resembled that of Experiment 1.

The experimental result

A total of twelve participants took part in the psychophysical experiment. To account for potential variations in brightness perception strategies among participants, extreme data points (criterion: standard deviation exceeding 3 sigma) were excluded from the analysis.

Figure 7 displays the comprehensive outcomes across all ambient conditions, encompassing the two AR devices. Participants perceived the total luminance entering their eyes to be brighter than the luminance of the white patch image displayed on the conventional monitor. This observation indicated a phenomenon similar to the transparent effect observed in Experiment 1. However, the extent of the transparent effect differed depending on the transmittance of the AR device. The transparent effect was more pronounced with lower transmittance of the AR glass. In essence, when using an AR glass with lower transmittance, participants selected a brighter white patch on the conventional monitor to match the same perceived brightness as the AR image under ambient conditions, compared to when using an AR glass with higher transmittance. This trend is illustrated in Table 1 and the accompanying figure.

Table 1. The coefficient values for two AR glasses

	transmittance	α	β
BT-100	70%	1.36	88.25
BT-300	35%	2.22	74.01

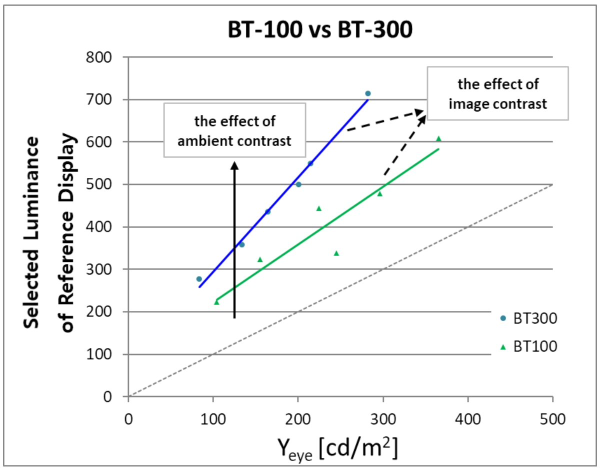

Figure 7. *Difference in brightness perception tendency by the transmittances of two device*

These findings underscore the significance of accounting for ambient contrast as a factor when assessing the contrast effect on the visibility of AR glasses employing half mirrors. It's important to note that the ambient contrast differs from the image contrast within the AR images, such as the contrast between white and black within a single image.

Conclusion

To investigate brightness perception of AR images and explore the impact of ambient contrast from the AR background, we conducted two psychophysics experiments. In Experiment 1, we observed the brightness of AR images using a single pair of AR glasses under various correlated color temperatures (CCTs) of the real-world background. In Experiment 2, we used two pairs of AR glasses with different transmittances (35% vs. 70%) and compared the brightness of the AR images. The results from the second experiment will shed light on the effect of ambient contrast from the AR background on brightness perception of AR images.

The findings revealed that participants consistently selected a brighter white patch on the conventional monitor to match the perceived brightness of the AR image in ambient conditions, irrespective of the CCTs of the ambient conditions. This outcome indicates that AR images in ambient conditions are perceived as brighter compared to 2D images with the same luminance displayed on the conventional monitor. Furthermore, this tendency became more pronounced with lower transmittance of the AR glasses. These results signify the necessity of considering an additional contrast effect based on the type of AR glasses used. There may be interaction effect between the ambient contrast and the image contrast in AR.

This phenomenon resonates with previous studies. Drawing from earlier research [5, 7-9], it is evident that brightness perception is influenced by various factors, including transparent displays and AR devices. Thus, there is a need to systematically comprehend different phenomena observed across various media and establish a unified theory.

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