Effects of Optical See-Through Displays on Self-Avatar Appearance in Augmented Reality

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Abstract

Display technologies in the fields of virtual and augmented reality affect the appearance of human representations, such as avatars used in telepresence or entertainment applications, based on the user's current viewing conditions. With changing viewing conditions, it is possible that the perceived appearance of one's avatar changes in an unexpected or undesired manner, which may change user behavior towards these avatars and cause frustration in using the AR display. In this paper, we describe a user study (N=20) where participants saw themselves in a mirror standing next to their own avatar through use of a HoloLens 2 optical see-through head-mounted display. Participants were tasked to match their avatar's appearance to their own under two environment lighting conditions (200 lux and 2,000 lux). Our results showed that the intensity of environment lighting had a significant effect on participants selected skin colors for their avatars, where participants with dark skin colors tended to make their avatar's skin color lighter, nearly to the level of participants with light skin color. Further, in particular female participants made their avatar's hair color darker for the lighter environment lighting condition. We discuss our results with a view on technological limitations and effects on the diversity of avatar representations on optical see-through displays.

Index Terms: Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality

1 Introduction and Related Work

While portraying imagery that is indistinguishable from reality is a common aim of augmented reality (AR) displays [8, 19], there are various present obstacles to this goal. OST AR displays are prone to limitations that arise due to their use of the additive light model to display virtual imagery [2, 7, 9, 10], where light emitted by the display is added to, and blends with, light originating from within the user's environment. Because of this, imagery on OST displays tends to take on some of the characteristics of the user's physical environment in a phenomena known as color blending, where the colors within the displayed imagery shift towards the colors in the user's environment [4–6, 9]. This effect can cause imagery to appear transparent, since regions intended to appear uniform in the AR imagery will appear to be non-uniform unless presented in front of a background of a solid uniform color. While future displays, such as subtractive light model displays [7] or displays with an opacification layer [1] hope to solve this problem by selectively occluding light from the user's environment, so far these methods have not yet been integrated into current OST displays.

Imagery shown on OST displays is also affected by the intensity, or luminance, of the lighting within the user's environment. Environment lighting can exaggerate the effects of color blending, where in the presence of particularly bright environment lighting, such as sunny outdoor lighting, the virtual imagery washes out and loses contrast. Erickson et al. [3] investigated this, where they found that even in moderate lighting conditions, the contrast between virtual imagery and the physical environment is reduced below accessibility standards, such as those recommended for viewing web content by the W3C [1]. In these reduced contrast conditions, it is likely that users will experience negative effects such as reduced legibility of text [14, 22] and reduced performance in search tasks [12, 15, 16]. The negative effects of environment luminance were also investigated by Zhang and Murdoch [21], where they demonstrated that perceived transparency can be predicted as a function of two contrast values: contrast within the virtual image to be displayed and contrast within the physical scene.

While it is easy to see how issues such as perceived transparency and low contrast could contribute to user difficulty in reading text or interacting with user interfaces, it is less intuitive to understand how these issues affect the user for other common types of imagery displayed on OST displays. For example, virtual humans are commonly displayed to represent the avatar of a remote user or system controlled agent [11, 17, 18, 20], and are similarly affected by issues of contrast and transparency. Peck at at. previously investigated how the issue of transparency affects user perception of virtual humans shown on additive displays, where they showed that participants perceived virtual humans that were more transparent to be less human [13]. Additionally, since darker colors appear more transparent on OST displays, virtual humans with darker skin tones were perceived by participants to be less human than virtual humans with lighter skin tones, implying that there may be an inherent racial bias in the presentation of humans on OST displays.

In this paper, we investigate whether participant decisions in an avatar creation task differ between different viewing conditions. In a user study (N=20), participants stood in front of a mirror that showed both their own reflection as well as their avatar and matched the appearance of their avatar to their own. We compared a comparatively dark environment (200 lux), in which dark colors could be better represented on the HoloLens 2, as well as a light environment (2,000 lux), in which the amount of light in the physical environment made it impossible to accurately represent dark colors on the OST-HMD.

In the brighter environment, participants are faced with the dilemma to either have parts of their body (e.g., skin or hair) appear

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[1] https://www.w3.org/TR/UNDERSTANDING-WCAG20/visual-audio-contrast-contrast.html

transparent or lighter than their actual body. We hypothesized that participants—especially those with dark skin colors or dark hair colors—would increase the lightness of these colors, effectively changing their appearance. We further hypothesized that the appearances of the resulting avatars created by all participants would converge on the same reduced (light) color palette.

2 EXPERIMENT

2.1 Participants

For this study, we recruited 20 participants: 13 male and 7 female, aged 18 to 55. Four of them self-identified as Black/African American, four as Asian, and twelve as Caucasian. The participants were students or members of the local university community. All participants were in STEM disciplines. The participants had normal or corrected-to-normal vision. When asked to assess their AR experience, five said they had none, nine said they had some, and six said they had a lot.

2.2 Materials

The physical setup is shown in Figure 1. We performed our experiment in a 2.1 m $\times$ 2.1 m isolated room.

Participants wore a Microsoft HoloLens 2 for the AR visual stimulus presentation (see Figure 1). The HoloLens 2 is an OST-HMD with a field of view of circa 54 degrees diagonally, a resolution of 47 pixels per degree of sight, and a refresh rate of 120 Hz. We used a UV CleanBox[2] to sanitize the equipment between use.

We placed a 0.6 m (wide) $\times$ 1.8 m (high) mirror in the experimental room in the center of one of the walls. By standing on a marked position slightly off-center in front of the mirror, participants could see their own reflection, while at the same time their avatar was presented via the OST-HMD in the mirror as if it was standing next to them in the experimental room.

The visual stimuli are shown in Figure 2. The environmental light in the experimental room could be varied. We used an Urceri MT-912 light meter to calibrate two environmental lighting levels (200 lux and 2,000 lux). This light meter is reported to have an accuracy of $\pm 3\%$ of the measured value, and can make measurements between one and 200,000 lux, as reported by the Urceri website[3].

The AR avatars were created in real time using the ReadyPlayerMe application and Unity API developed by Timmu Tõke[4]. Skin colors and hair colors were adjusted by participants by requesting relative changes from their experimenter, i.e., increasing or decreasing the lightness of the colors using the palette shown in Figure 2.

2.3 Methods

In this experiment, we used a mixed design with one within-subject factor and two between-subject factors. Our within-subject factor was *environment lighting*, which had two levels: The amount of environment light was either 200 lux, which represents the amount of light in a common dark indoor office environment, or 2,000 lux, which represents dim outdoor lighting such as on a cloudy day. We further considered the between-subject factor *skin color*, which, due to the limited diversity of our participant sample, we simplified for our analysis to just two levels: dark and light. Similarly, we considered the between-subjects factor *gender*, which we again simplified to just two levels: female and male. Each participant completed all conditions in random order.

2.3.1 Measures

In this experiment, we had two main measures:

[2]https://cleanboxtech.com

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

[4]https://readyplayer.me

Figure 1: Experimental setup: Person standing on a marked location in the experimental room in front of the mirror wearing a HoloLens 2.

- *Selected skin color*: When matching the appearance of their avatar to their own reflection in the mirror, participants selected the skin color of the avatar on a ten-level scale (1=dark to 10=light; see Figure 2 c).
- *Selected hair color*: Participants further selected the hair color of the avatar on a ten-level scale (1=dark to 10=light; see Figure 2 d).

2.3.2 Procedure

Prior to the experiment trials, participants gave their informed consent. Participants then received a brief overview of what AR displays are, as well as what their task in this experiment will be. We then took a picture of the participants to auto-generate an approximate avatar look-alike using the ReadyPlayerMe software.

Participants were then asked to stand in front of the mirror at the marked location on the floor. Once participants donned the HoloLens 2, an AR avatar appeared next to them in the mirror. Participants were then instructed to adjust the appearance of their avatar. The participants could fine-tune the appearance of their avatar as supported by the ReadyPlayerMe software, e.g., by choosing its clothes and hair style.

The main conditions of the experiment were tested in random order, where the environment lighting was either set to 200 lux or 2,000 lux. In each of these lighting conditions, the participants were asked to adjust their skin color and their hair color to make their avatar match their own reflection in the mirror. The initial skin/hair colors for these trials were randomized between the maximum or minimum lightness levels on the ten-level palette.

3 RESULTS

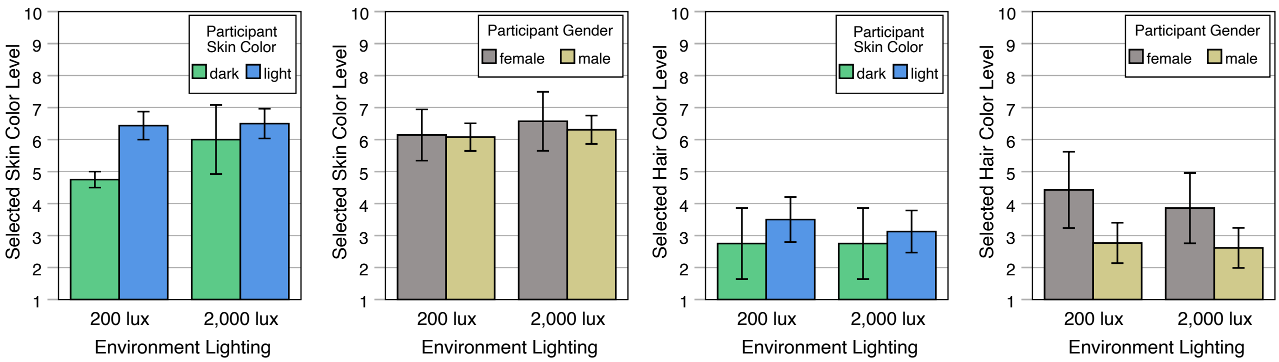
Figure 3 shows our results for participants' selected skin color and hair color levels for our within- and between-subject variables.

We analyzed participants' selections on the skin color and hair color scales using parametric tests at the five percent significance level, after testing for all assumptions of these tests. For independent variables, we considered the two between-subject variables participants' *skin color* and *gender*, and the within-subject variable *environment lighting*. We only report the significant results.

We first looked at the effects of our between-subject variables using one-way ANOVAs. For participants' *skin color*, we found a trend for the *selected skin color levels*, $F(1,38) = 2.51$, $p = 0.12$, $\eta_p^2 = 0.06$, and no effect on the *selected hair color levels*, $F(1,38) = 0.31$, $p = 0.58$, $\eta_p^2 = 0.01$. For participants' *gender*, we found a trend for the *selected hair color levels*, $F(1,38) = 3.01$, $p = 0.09$, $\eta_p^2 = 0.08$, and no effect on the *selected skin color levels*,

(a) (b) (c) (d)

Figure 2: Experimental stimuli: Screenshot of a person's view through the HoloLens 2 taken with Microsoft's HoloLens Mixed Reality Live Preview (i.e., close but not a completely accurate representation of participants' view) in the (a) 200 lux condition and (b) 2,000 lux condition, and the color palettes for (c) skin color and (d) hair color.



(a) (b) (c) (d)

Figure 3: Bar charts showing effects of environment lighting on avatar (a+b) skin colors and (c+d) hair colors on ten-level scales (1=dark to 10=light). Plots (a+c) show results for our participants' between-subject factor skin colors, and plots (b+d) show them for participants' gender.

$F(1,38)=0.08$, $p=0.78$, $\eta_p^2=0.002$. Considering the trends together with the limited between-subject samples in our experiment, which suggest that the statistical power may not have been high enough to show significant effects, we decided to perform our further analysis by modeling these between-subject factors separately.

First, looking at *skin* colors, we analyzed our results with a two-way mixed ANOVA model with the within-subject factor *environment lighting* and participants' between-subject *skin color*. We observed a trend though no significant interaction effect between *environment lighting* and participants' *skin color* on the *selected skin color levels*, $F(1,18)=4.13$, $p=0.057$, $\eta_p^2=0.19$. We found a significant main effect of *environment lighting* on the *selected skin color levels*, $F(1,18)=5.04$, $\mathbf{p}=\mathbf{0.038}$, $\eta_p^2=0.22$.

Second, looking at *hair* colors, we analyzed our results with a two-way mixed ANOVA model with the within-subject factor *environment lighting* and participants' between-subject *gender*. We observed no significant interaction effect between *environment lighting* and participants' *gender* on the *selected hair color levels*, $F(1,18)=1.52$, $p=0.23$, $\eta_p^2=0.08$. We found a significant main effect of *environment lighting* on the *selected hair color levels*, $F(1,18)=4.58$, $\mathbf{p}=\mathbf{0.046}$, $\eta_p^2=0.20$.

4 Discussion

Overall, our results give interesting insights into the limitations of OST-HMD technologies. In particular, our results indicate that for some participants the amount of light present in the physical environment affected how they perceived their own avatar in AR, causing them to adjust their avatar's appearance.

Skin Color When asked to match their avatar's skin color to their own, we found a significant effect of environment lighting on the skin colors participants selected when creating their avatar. Our results (Figure 3 a) indicate that participants with a dark skin color selected a dark skin color for their avatar when the physical environment was dark (200 lux), but they had to make their avatar's skin color lighter when the physical environment was well-lit (2,000 lux). On average, their selected avatar skin colors in the well-lit physical environment were very close to those selected by participants with a light skin color. In contrast, we did not observe such an effect for participants with a light skin color—their avatar's skin color remained largely the same between the two physical lighting levels.

This effect may be explained by a major limitation of current OST display technologies, including the HoloLens 2 we used in our experiment. With OST displays based on the additive light model, light can be added to the user's view of their physical environment, but not reduced. Hence, it is not possible to present anything on an OST display that is darker than the physical background seen through the display. If a participant's skin color was darker than the physical background, they had the choice to either appear "transparent" [13] or to increase their skin color to improve contrast between their avatar and their physical environment. While the latter ensured that they would be visible on the display, this caused the appearance of all participants' avatars to converge on the same (light) skin colors, independently of what skin color they really have. These results are concerning, considering that the display technology may greatly reduce the diversity of avatars presented on those displays in future applications where multiple users and avatars occupy the same AR space.

Hair Color We observed another interesting effect when we asked participants to match their avatar's hair color to their own. Our results (Figure 3 d) indicate that in particular female participants gave themselves a darker hair color in the well-lit environment compared to the dark environment. In contrast to our results for skin colors, the selected hair colors overall were comparatively dark.

As the direction of the effect for hair color is opposite to the effect for skin color, this effect could potentially be explained by participants trying to maximize the light differential between their skin color and their hair color. As for skin colors, when asked to match their appearance, participants had the choice to either have dark colors appear transparent or to increase their lightness. With participants' hair colors starting off as comparatively dark, a slight increase in lightness would not have effected a major change in transparency. It stands to reason that participants would not have given their avatar a very light hair color (e.g., blonde) just to make their hair more visible on the display. Instead, it appears that they rather tried to make it as dark as possible (i.e., transparent) considering the amount of environment light defining a natural lower bound to its appearance. That this effect was more pronounced for our female participants may be due to women often having longer hair than men, filling a larger portion of their view on the display.

Implications As OST displays begin to reach consumers for general usage, users will find themselves in many different environments ranging from dim nighttime or interior lighting conditions to outdoors in direct sunlight. Until the displays are capable of automatically adjusting factors, such as luminance output and attenuation, to maintain the perceived appearance of virtual imagery in different environment conditions, virtual imagery, including the user's representation as a virtual avatar, will need to be able to adapt appropriately to best maintain the user's desired representation. Existing AR applications involving avatars typically use a one-off avatar creation process that does not consider how user perception of the avatar will change according to the observer's viewing conditions. Our results indicate that users may wish to have the option to manually specify how they will be represented by their avatar for different viewing conditions, or may wish to have the system automatically adjust the appearance of their avatar, potentially interpolating between different user created or system generated versions of their avatar.

Limitations Our experiment has different limitations. First, our participant sample (N=20) was not large enough to provide us the required statistical power to show all between-subject effects. Future work should focus on very large and diverse participant samples to elucidate the underlying demographical and appearance-related factors. Second, our results are specific to the HoloLens 2 HMD. While current developments among commercial OST-HMDs aim to increase the maximum luminance of the display, this will not change the underlying problem that colors darker than the user's environment cannot be displayed due to the additive light model. Future work should focus on the development of prototypical mechanisms such as pixel-wise light subtraction/attenuation for OST-HMDs (e.g., [7]). Third, our experiment was limited to only two levels of environment lighting (200 lux and 2,000 lux). Future work should consider dynamic ranges from dark indoor environments to sunny outdoor lighting, which can reach upwards of 100,000 lux, which would likely amplify the issues observed in our experiment.

5 Conclusion and Future Work

In this paper, we investigated how users wearing an OST-HMD choose the appearance of their own avatar under different physical lighting conditions. We conducted a user study (N=20) where participants saw themselves in a mirror side-by-side with their own avatar, seen through a HoloLens 2 display. Participants then were tasked with matching their avatar's appearance to their own. Our results show that the amount of environment light had a significant effect on the selected skin colors of our participants' avatars. Especially for participants who have a dark skin color, the lighter physical environment caused them to make their avatar's skin color lighter, nearly to the level of those participants who have a light skin color. Further, we observed that in particular female participants made their avatar's hair color darker for lighter physical environments. While these observations are concerning as they can limit the diversity of avatar representations on such OST displays, future work with larger sample sizes and a wider range of demographics is needed to fully elucidate these issues and to identify technological and/or other means to ameliorate them.

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