Color and Brightness in Optical See-Through Augmented Reality Display Systems

Michael J. Murdoch

michael.murdoch@mail.rit.edu
Munsell Color Science Laboratory, Rochester Institute of Technology,
54 Lomb Memorial Dr., Rochester, NY, 14623 USA
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ABSTRACT

Optical see-through augmented reality (OST-AR) display systems use a transparent display to combine virtual AR components with the real background, leading to color and brightness distortions of both the AR and the background. Experiments show that visual matches do not consistently correspond with physical matches, and a discounting model is proposed.

1 INTRODUCTION

Augmented reality (AR) offers the tantalizing capability to mix virtual content, such as avatars, overlays, graphics, and text, into the same field of view as real-world environments [1]; this could be extremely valuable in applications including medicine, education, telepresence, and gaming. Optical see-through AR (OST-AR) employs a transparent display that shows the virtual content while providing a relatively undistorted view of the real world behind it. An alternative is video see-through (VST-AR), which combines via alpha-matting the rendered virtual content with a live view of the real world as captured with a camera.

Focusing on OST-AR, a generally positive aspect of the transparent display is an unmediated real-world view, but a related negative aspect is its inability (with current technology) to occlude real-world background objects behind. This means that the background bleeds through virtual content, distorting its appearance, and makes OST-AR difficult to use in bright environments.

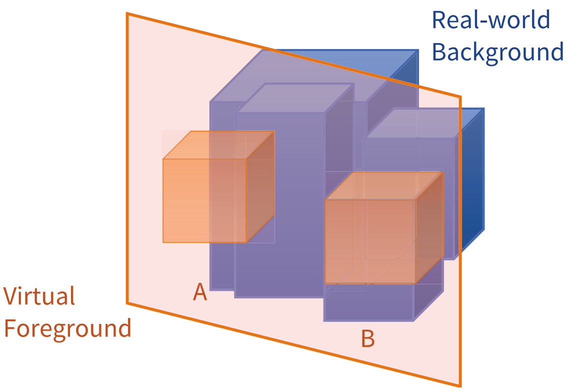

Figure 1: Diagram of OST-AR showing virtual cubes (in orange) on a transparent display overlaid upon real-world background objects (in blue).

Figure 1 shows a conceptual diagram of OST-AR, in which two virtual cubes are overlaid on a real-world background, visible behind the transparent display. Two use cases are illustrated: cube A appears as a virtual cube in front of the background, as an avatar or virtual object might be added to a scene; while cube B is aligned with a background cube, where it can appear to merge with and manipulate the real-world material properties.

1.1 OST-AR Displays and Optics

OST-AR systems are generally head-mounted displays (HMDs), also called near-eye displays (NEDs), but not the opaque type used for virtual reality. Instead, the view of the real world is preserved by utilizing an optical combiner that relays the light from a small, often OLED, micro-display to the user's eyes. Optical combiners may take the form of curved beamsplitters, freeform prism optics, or holographic waveguides [2].

NED-based OST-AR optical system designs remain challenged to meet competing objectives of large field of view, large exit pupil or eye box, high brightness, high resolution, small size, low power, etc. Further, because of the small exit pupil and close eye position, optical measurements require specialized hardware [3]. Future design of OST-AR systems should be guided by perceptual characteristics and limitations, but a full understanding of these requires further research.

1.2 Perceptual Effects of OST-AR

Several researchers have addressed the visual results of OST-AR systems, starting with the physics and colorimetry of the optical blend [4][5]. However, the perception of transparent AR stimuli overlaid on real-world background scenes is not straightforward. Full physical compensation is difficult and in some cases perceptually incorrect; meanwhile, color appearance models, designed for reflective and displayed color stimuli, do not account for transparency [6]. Virtual AR overlays add light to a scene via the emissive, transparent display, which means that the visual cues of the percept of transparency are confounded with brightness, and our usual understanding of scene illumination is distorted. Fundamental findings on transparency and brightness are helpful but not sufficient to describe the perception of OST-AR situations [7][8][9].

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2 EXPERIMENTS AND MODEL

The author's group's current research addresses the visual perception of overlaid virtual stimuli through color and brightness matching experiments, and the results of recent experiments provide ground truth for appearance in AR situations against which models may be tested. In general, all combinations of matching between and within stimuli in the AR foreground and real-world background require investigation. With that in mind, a research OST-AR setup was constructed in the Munsell Color Science Laboratory. The desktop-scale setup utilizes a conventional LCD with a large glass beamsplitter as an optical combiner in front of a light booth, as shown in Figure 2. The arrangement can present viewers with arbitrary combinations of real-world background objects (cube in the light booth at right, blue arrow) and virtual AR foreground stimuli (generated by the LCD at bottom, red arrow). This relatively large, *not* head-mounted system is much easier to measure and calibrate than a HMD. An updated setup is presently being constructed with a high-brightness LCD and a more versatile LED lighting system.

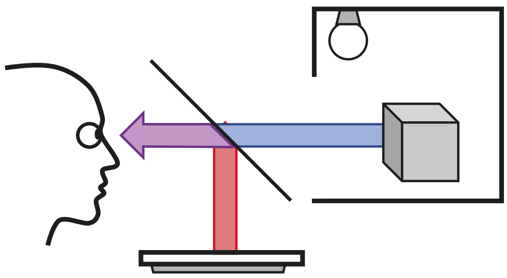

Figure 2: Research OST-AR setup that combines virtual stimuli from an LCD (bottom, red arrow) with real-world objects (right, blue arrow) using a beamsplitter (diagonal line).

2.1 Experimental Results

Details of several experiments have been reported elsewhere [10][11][12]; here, an overview is provided. One type of experiment involved color matching AR foreground stimuli with different backgrounds; some of the stimuli are shown in Figure 3. In each panel, the pair of smaller patches are presented by the transparent AR display with the same video drive values. They appear different from one another because of the background patch colors bleeding through. Observers were asked to adjust the color of the patch on black to match its partner on the other background, and the results show that a visual match is not the same as simply undoing the optical bleed-through. The visual system seems to discount the background to some extent while matching AR foreground stimuli. A similar experiment was done with more complex, rendered foreground objects and found a similar result with even stronger discounting.

Another experiment utilized real 3D cubes as a background scene combined with AR foreground overlays, as shown in Figure 4. Observers were asked to match the brightness of the cube plus overlay to the brightness of a different, lighter-gray cube. Observers were able to interpret the overlay as a modification of the surface reflectance of the cube, making a physical luminance match in cases like panel A and B where the AR overlay was tightly-fit to the 3D cube behind. With oversized overlays, as in panels C-E, observers required more AR light than a physical match to make a brightness match, implying that they were discounting the impact of the AR overlay, to some extent. With an undersized overlay, as in panel F, they used less light than a physical match, similar to the previous foreground-matching experiments.

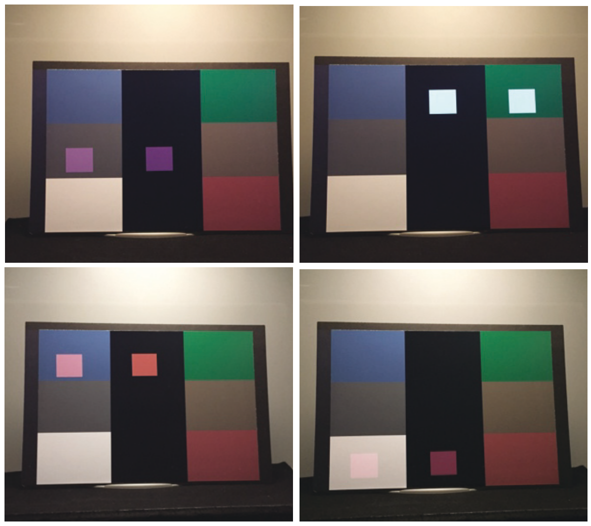

Figure 3: AR color matching stimuli examples. Each panel shows a pair of small AR foreground color patches overlaid on larger, printed background patches in a light booth.

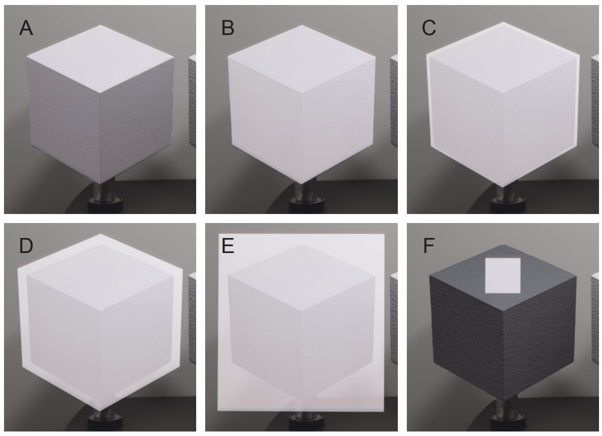

Figure 4: AR brightness matching stimuli examples. Panels A-F show different AR overlays upon a background, real 3D gray cube.

2.2 Foreground-Background Discounting Model

The results of these matching experiments have given support to simple visual discounting model inspired by the literature on transparency perception:

$$XYZ_{eff} = \alpha\, XYZ_{FG} + \beta\, XYZ_{BG} \qquad (1)$$

Working in linear colorimetric tristimulus values (*XYZ*), the model suggests that the effective *XYZ*, that of the visual match, is a weighted sum of the foreground (FG) *XYZ* and background (BG) *XYZ* with weighting scalars α and β, respectively. Because the transparent AR display simply adds light to the scene behind, a physical solution to this equation would require $\alpha = \beta = 1$. However, the physical solution does not create a visual match; discounting either the foreground or the background would result in a relatively smaller value of the corresponding weighting scalar, with the other having a greater contribution to the perceived color.

In the experiments completed to date, the extent of visual discounting, and thus the relationship between α and β, seems to depend on the matching task and the complexity of the stimuli. In the foreground-matching experiments (as in Figure 3), the background was discounted, resulting in $\alpha : \beta$ ratios of between 2:1 and 3:1. In the cube-matching experiment (as in Figure 4), the AR foreground was discounted according to the size of the AR overlays, resulting in $\alpha : \beta$ ratios from nearly 1:1 for overlays A and B to 0.7:1 for overlays D and E.

A related experiment conducted by Chen and Wei, which asked observers to adjust an AR overlay to as neutral (or white) as possible in front of backgrounds with different CCT illumination also seems to show a discounting effect, though this model was not specifically applied [13]. They found that at lower light levels, the background CCT had minimal effect on the color setting of the AR foreground. At higher light levels the background effect was stronger, but not complete – they attribute this to incomplete adaptation, but background discounting would result in a similar effect.

3 DISCUSSION AND FUTURE WORK

Further experiments are required to verify or improve the foreground-background discounting model approach. For it to be useful in AR systems, a systematic approach must be developed to determine α and β values depending on the visual task and the complexity of foreground and background elements. Experiments to inform and develop this model are planned by the author's group in the near future, and collaborators with good ideas are welcome.

Once the perceptual response to OST-AR foreground-background stimuli in a variety of environments is better understood, a next step is developing color correction algorithms that are responsive to the user and to changes in the environment. This will likely require improvements to displays and sensors coupled with algorithms structured like those in computer graphics shaders. A display system "wish list" item that would minimize the bleed-through issue would be a compact system for selective optical occlusion of background areas.

4 CONCLUSIONS

The transparent displays of OST-AR systems provide valuable application-based solutions, but also generate some unique perceptual issues. Visual experiments conducted to date show that the physical bleed-through of background scene elements in OST-AR systems cannot be corrected by simple physical compensation. Instead, evidence supports a visual discounting mechanism whose behavior depends on the details of the situation and which can be modeled with a simple linear weighting of the contributions of real-world background and AR foreground elements.

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