Color Blending in Outdoor Optical See-through AR: The Effect of Real-world Backgrounds on User Interface Color

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When viewing augmented reality (AR) through an optical see-through head-mounted display (oHMD), the colors of AR elements become washed out as the luminance of the background increases. In addition, the colors of AR elements can shift and change depending on the color of the background that the AR elements are seen against. Both of these phenomena result from the way the color of an AR element blends with the color of the real-world background that the AR element is seen against. Although the fact that this color blending occurs is generally known, to date it has not been systematically studied or quantified. In this work, we sought to quantify this color blending by building an apparatus that allows precise and repeatable color measurements, and then conducting an empirical engineering study.

Apparatus: Figure 1 shows our apparatus; the top view is a schematic diagram while the bottom view is a photograph. Our enclosure houses two fluorescent lights that reproduce the daylight whitepoint D65; our bulbs are rated at 95 CRI, which indicates that they accurately reproduce the entire daylight spectrum. The enclosure sits against a frame that holds either (1) a *real-world background*; a sample of common outdoor material against which an AR element might be seen (Figure 2, top row), or (2) a *poster* that has been painted to match the color of a real-world background item (Figure 2, bottom row). Light from the illuminated background flows through an AR oHMD monocle. We flooded the monocle with the 27 AR colors formed by every combination of red, green, and blue at the levels of 0, 128, and 255; for the color black (0,0,0) we turned off the oHMD. These colors systematically sample the possible oHMD color gamut. The light next exits the monocle, its color a blend of the background color and the AR color: the color that an AR user would experience. The light then flows through a magnifying lens from an SLR camera, and finally into a colorimeter.

Experiment: We examined how the colors of the 11 backgrounds in Figure 2 blended with the 27 AR colors. Our experiment had two control conditions: (1) we turned off the testbed lights and therefore measured each unblended AR display color, and (2) we turned off the oHMD and therefore measured each unblended background color. It also had three whitepoints: (1) the white poster, (2) the oHMD flooded with the color white, and (3) the oHMD flooded with white against the white poster. Overall, we collected 296 data points, which encompass every possible background color by AR color combination.

Our colorimeter reported these color values in CIE 1931 *xyY* format. Normalizing over our three whitepoints, we transformed these *xyY* values into the CIE 1976 *u*'*v*' and *L***u***v** color spaces. As shown in Figures 3 and 4, the *u*'*v*' values allowed us study how the chromatic experience of viewing each AR color changed when shifting from one background to another. The *L***u***v** values are within an approximately perceptually linear 3D color space, which allowed us to quantify how much the AR colors changed when seen against different backgrounds.

To study these changes, we created graphs like those in Figures 3 and 4 for all 55 background pairs. The white arrows on each graph show how the 27 AR colors change in *u*'*v*' space when we shift from the first to the second background, while the stacked bar on the bottom of each graph panel shows the mean overall change in *L***u***v** space; the pink portion is the luminance change (*L**), and the blue the chromatic change (*u***v**). We printed and cut out the 55 graphs and grouped and organized them, looking for patterns and categories that qualitatively describe groups and trends in the way the AR colors change.

Results: Our analysis revealed 4 qualitatively different categories; Figure 3 shows an example from each category: (3a) *Washout due to chromaticity*: When seen against a very dark background, the AR colors span a large *u*'*v*' chromatic area: presumably many different colors could be recognized. However, when seen against a very bright background, the AR colors cluster tightly in the middle of *u*'*v*' space; presumably they would appear washed out and perceptually indistinct. (3b) *Washout mostly due to luminance*: When seen against two different bright backgrounds, the AR colors remain tightly clustered and hence washed out; most of the perceptual change is in the luminance of the AR colors. (3c) *Washout due to both chromaticity and luminance*: Many background pairs result in a perceptual effect that blends categories 3a and 3b, where the amount of luminance and chromaticity change is approximately even. (3d) *Linear chromaticity shift*: When shifting from one strongly colored background to another, AR colors linearly shift in chromaticity, with no real change in luminance. Presumably AR colors could shift enough that users would see them as being qualitatively different; for example in Figure 3d yellows shift into oranges and blues shift into purples.

We also compared real backgrounds and posters that we painted to match backgrounds (Figure 2, first three columns); this comparison tests the validity of using painted posters to study AR color blending. Figure 4 shows these results, which generally fall into category 3d and exhibit a relatively small linear chromaticity shift.

Previous Work: We have previously reported an engineering study [1] in which we used a preliminary version of the apparatus described here. However, this previous apparatus could only accommodate posters that were painted to match a background color (e.g., Figure 2, bottom row). This is the primary limitation of our previous work: with posters, the colors of background objects can only be matched *metamerically*, where the two colors are perceived to be the same color, but the waveforms are different. However, our current results suggest that painted posters result in qualitatively similar results to real-world background materials. In addition to an improved apparatus, in our current study we also improved the way we processed and analyzed our measured data.

References

[1] Gabbard JL, Zedlitz J, Swan II JE, and Winchester III WW, "More Than Meets the Eye: An Engineering Study to Empirically Examine the Blending of Real and Virtual Color Spaces", *Proceedings of IEEE Virtual Reality 2010* (Waltham, MA, USA, 2010), pp. 79–86.

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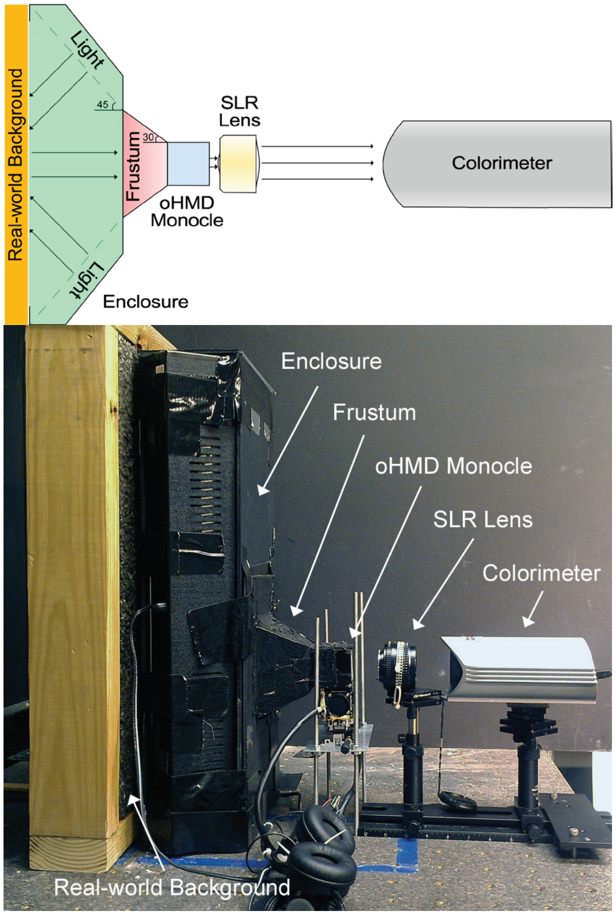
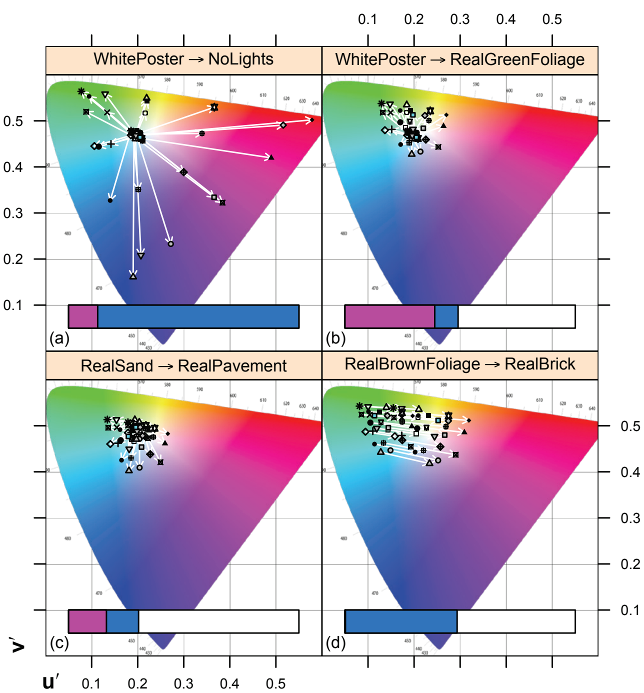
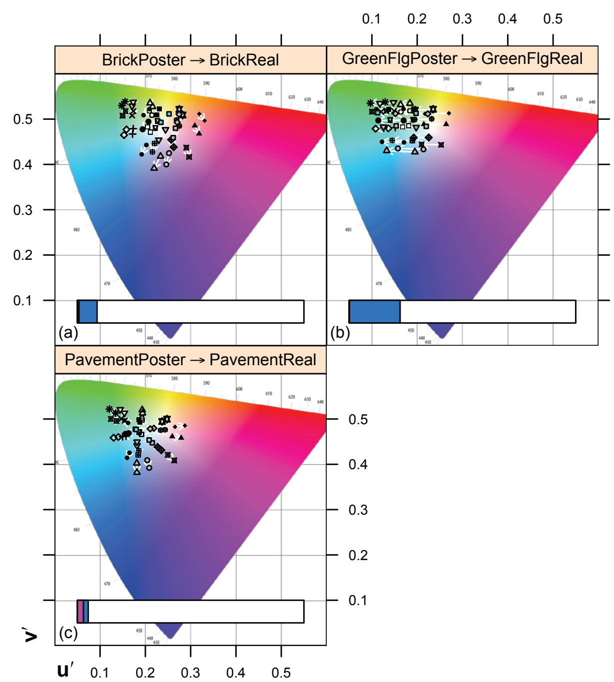


▲ **Figure 2.** We created five real-world backgrounds using physical materials (top row), and four painted posters, as well as a blank poster for the *white* condition (bottom row). The eleventh background was a no-lights condition. The first three columns compare real-world backgrounds and posters painted to match the same background.

◄ **Figure 1**. (Above) A top view schematic of our experimental testbed, depicting an enclosure (green) containing two 15-watt lights reflecting off of real-world or poster backgrounds (orange). Indirectly reflected light exited the enclosure through the frustum (red), and into the AR oHMD monocle (blue). The light then left the monocle and entered an SLR camera lens (yellow). Leaving the lens, the light entered the colorimeter (grey). (Below) An annotated photograph of our optical experimental testbed shown with pavement material as the real-world background.



▲ **Figure 3**. Pairwise visual analysis of background pairs: each arrow shows how an AR color shifted when moving from the first to the second background. The stacked bars quantify the perceptual change in *L***u***v** space; the pink portion is the luminance change (*L**) and the blue the chromatic change (*u***v**). Each panel is an example from one of the four major categories that we discovered (see text).



▲ **Figure 4.** Pairwise visual analysis of the three real-world background and painted poster pairs. Each panel is an example from the *linear chromaticity shift* category. Note the minimal color change between the real and poster versions of these backgrounds, which is especially notable considering that the painted posters are only a metameric color match against the real-world backgrounds.