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Adapting Michelson Contrast for use with Optical See-Through Displays

Austin Erickson* Gerd Bruder† Gregory F. Welch‡

University of Central Florida

Abstract

Due to the *additive light model* employed by current optical see-through head-mounted displays (OST-HMDs), the perceived contrast of displayed imagery is reduced with increased environment luminance, often to the point where it becomes difficult for the user to accurately distinguish the presence of visual imagery. While existing contrast models, such as Weber contrast and Michelson contrast, can be used to predict when the observer will experience difficulty distinguishing and interpreting stimuli on traditional displays, these models must be adapted for use with additive displays. In this paper, we present a simplified model of luminance contrast for optical see-through displays derived from Michelson's contrast equation and demonstrate two applications of the model: informing design decisions involving the color of virtual imagery and optimizing environment light attenuation through the use of neutral density filters.

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

1 Introduction

Optical see-through head-mounted displays (OST-HMDs) allow users to view virtual imagery superimposed over their view of their physical surroundings. These devices use what is commonly known as the *additive light model*, since the light emitted by the display is added with the light originating from within the user's environment [7]. This blending of light leads to virtual imagery appearing transparent on this type of display [6, 13], where contrast between displayed imagery and the user's environment decreases with increased environment lighting [4].

Poor contrast leads to usability and perceptual issues where the observer may be unable to accurately distinguish visual features within the virtual imagery (e.g., reading text on the display), and in extreme cases, such as sunny outdoor lighting conditions, the user may not even be able to recognize the presence of the virtual image at all [8, 11, 14]. By identifying when problematic conditions occur, we set the stage for potential methods that improve image quality, whether these methods rely on high-level software-based contrast improvement strategies, changes made within the user's environment, or more fundamental changes to the underlying design of the display and optics. For this reason, it is important to be able to recognize when environment conditions are likely to interfere with the user's ability to perceive virtual imagery shown on optical see-through displays.

*ericksona@knights.ucf.edu
†bruder@ucf.edu
‡welch@ucf.edu

2 Luminance Contrast Model

While there are several commonly used contrast models, such as Michelson contrast [10] (see equation 1 below), these models must be adapted to consider how the factors specific to optical see-through displays affect user perception of contrast by introducing separate terms for describing the displayed imagery, the display itself, and the user's environment [3, 9].

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

$$C = \frac{|\mathbf{a}(\mathbf{x}-\mathbf{y})^T|}{\mathbf{a}(\mathbf{x}+\mathbf{y})^T + 2kI_{env}} \tag{2}$$

Our adapted contrast model for OST displays is presented in equation 2, with its parameters defined as follows:

$\mathbf{a} = [I_r, I_g, I_b]$: A row vector representing the perceived illuminance from the observer's eye position of the red, green, and blue color channels respectively, at maximum intensity in a pitch dark environment. Each of these values can be measured via use of an inexpensive light meter.

$\mathbf{x}, \mathbf{y} = [r, g, b]$: Row vectors containing the RGB values of the two colors being compared. While most displays use a gamma correction function that would need to be considered in this input term, such as the one defined in the sRGB standards [1], this simplified version of the model assumes that the perceived brightness of imagery is linear with respect to increasing RGB value.

k: The attenuation factor of the display, which can be determined as a ratio between environment light measured through the OST display powered off and environment light I_{env} from the user's position.

I_{env}: The illuminance from the observer's position of the lighting in the physical environment. This value can be looked up from a table of common environment lighting conditions[1], or can be measured from the user's position via a light meter.

The final form of the equation can be used to predict luminance contrast values between any pair of RGB color coordinates in the display's color space.

2.1 HoloLens 2 Model Parameters

We made photometric illuminance measures on the Microsoft HoloLens 2 to demonstrate how the input parameters for the contrast model can be found. These illuminance measures consisted of direct measurements of environment lighting as well as measurements made from the user's perspective within the display, and are shown in table 2.1. From these values we calculated the input parameters for our contrast model that are specific to the HoloLens 2 are: $\mathbf{a} = [35, 96, 31]$ and $k = 0.286$.

3 Discussion

Our contrast model can be used to calculate two main types of contrast related to OST displays: *physical-virtual contrast* and *virtual contrast*, as shown in figure 1.

Physical-virtual contrast is essentially a measure of how easily distinguishable AR imagery will be from the user's view of their physical environment through the display. For this specific type of

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

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Table 1: Table depicting the measured illuminance values made from the user's perspective within the HoloLens 2.

Environment Illuminance (lx)	Displayed Color (R,G,B)	Illuminance (lx)
0	(1,0,0)	35
0	(0,1,0)	96
0	(0,0,1)	31
1000	(0,0,0)	286

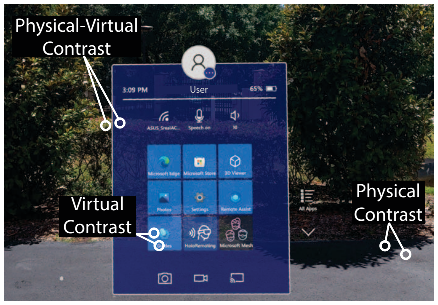

Figure 1: Three types of contrast comparisons can be made from the observer's perspective within an OST AR display. Physical-virtual contrast compares between a point in the AR imagery and a point in the observer's physical environment, in this case between the floating panel and the bushes behind it. Virtual contrast compares between two points within the AR imagery, in this case between the white text and blue background. Finally, physical contrast compares between two points in the observer's physical background.

contrast, one input color **x** for the contrast model can be set to any color on the border of the virtual imagery while the other color **y** is set to black. By setting the second color to black, where no light is emitted by the display, we calculate contrast between a point in the virtual image **x** and a point in the user's view of their physical environment **y**. Such calculations may be useful for estimating how salient a virtual image is, which may help in the design of effective attentional cues for OST displays [2].

For *virtual contrast*, two colors within the virtual imagery are compared, which is particularly useful for determining how well visual features (such as text or symbols) displayed in a certain color **x** stand out from a virtual background color **y**. Such contrast calculations may be helpful for choosing effective colors for UIs on OST displays. However, such calculations would come out to be equal for UIs with identical colors but different contrast polarities (black on white versus white on black), for which benefits have been demonstrated in the past for using negative polarity UIs over positive polarity UIs [5].

The contrast of various color combinations for an input set of display parameters can be compared to a desired contrast value, for example accessibility guidelines made by the W3C recommend a minimum simple contrast ratio of 4.5 to 1 for reading web-based virtual content, which when converted to Michelson contrasts refer to values of 64%. We recommend using this value as a starting point for a general guideline for making UI color design decisions for applications on OST HMDs. However, future work should specifically evaluate contrast standards for various tasks on OST displays, since there are many factors that influence user perception of virtual imagery that do not necessarily apply for more traditional displays [9].

For practical use cases, the brightest of sunny outdoor lighting conditions (near 130,000 lx) represents the maximum environment illuminance likely to be observed on an OST AR display [12]. Without significant attenuation, most displays are likely going to have a much smaller range of environment lighting conditions in which the contrast of the displayed imagery is at acceptable levels. The model presented in this paper can be used to calculate the upper bound of this range by specifying a desired contrast, for example the 64% recommended by W3C, and setting the input **x** and **y** RGB values to the maximum range using values of (1,1,1) for white and (0,0,0) for black. Then the equation can be rearranged to solve for I_{env} to find the maximum environment lighting that the particular display can be used in while meeting the desired contrast value.

The model can also be used to evaluate the effects of manipulating the attenuation factor k, in different environment lighting conditions. For example, the equation can be rearranged to find the minimum k for a desired contrast level, striking an optimal balance between reduced contrast in the user's physical environment and improved contrast in the virtual imagery:

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