HUE-SHIFT MODELING AND CORRECTION METHOD FOR HIGH-LUMINANCE DISPLAY

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ABSTRACT

The human eye usually experiences a loss of color sensitivity when it is subjected to high levels of luminance, and perceives a discrepancy in color between high and normal-luminance displays, generally known as a hue shift. Accordingly, this paper models the hue-shift phenomenon and proposes a hue-correction method to provide perceptual matching between high and normal-luminance displays. To quantify the hue-shift phenomenon for the whole hue angle, 24 color patches with the same lightness are first created and equally spaced inside the hue angle. These patches are then displayed one-by-one on both displays with different luminance levels. Next, the hue value for each patch appearing on the high-luminance display is adjusted by observers until the perceived hue for the patches on both displays appear the same visually. After obtaining the hue-shift values from the color matching experiment, these values are fit piecewisely into seven sinusoidal functions to allow hue-shift amounts to be approximately determined for arbitrary hue values of pixels in a high-luminance display and then used for correction. Essentially, an input RGB image is converted to CIELAB LCh (lightness, chroma, and hue) color space to obtain the hue values for all the pixels, then these hue values are shifted according to the amount calculated by the functions of the hue-shift model. Finally, the corrected image is inversely converted to an output RGB image. For evaluation, a matching experiment was performed using several test images and z-score comparisons.

Index Terms— High luminance displays, Bezold-Brücke effect, Hue shift

1. INTRODUCTION

Recently developed displays have an improved gamut, resolution, and luminance. In particular, the maximum luminance for the latest displays is about 400cd/m2 to 1,000cd/m2, which is almost four times that for most normal CRT displays. Thus, when two patches with the same chromaticity are observed on high and normal luminance displays, the patches are perceived as different from each other. This phenomenon is called the hue-shift effect, caused by a variation in the LMS cone sensitivity of the human eye due to the change in the patch luminance.

Bezold-Brücke[1] was the first to report on the hue-shift effect for a monochromatic stimulus with a change in luminance. Weale[2] and Vos[3] then interpreted this effect in terms of the adaptation of the photopigment. According to their theory, the cone that is most sensitive to the input stimulus is adapted as the intensity of the stimulus increases. As a result, the perceived hue is changed by varying the ratio of cone activities. Following this research, a lot of hue-shift results have been reported. Purdy[1] presented some typical experimental results on the Bezold-Brücke hue shift with a monochromatic stimulus. More recently, R.W.G. Hunt[4] applied the Bezold-Brücke hue shift to the Hunt 94u color-appearance model using a single patch to explain that the variation in the hue depended on the luminance change. Meanwhile, Ralph W. Pridmore[5] reported that explaining the hue shift using a single patch was limited, and insisted that the effect should be investigated using color-matching experiments with two patches.

However, the hue-shift model for monochromatic stimuli used by previous researchers is not appropriate for direct application to high-luminance displays, as the colors of high-luminance displays have a wide spectral distribution within the visible spectrum region. Accordingly, this paper models the hue-shift phenomenon with respect to a high-luminance display that has a wide spectral property, and proposes a hue-correction method to allow the hues on high and normal-luminance displays to be perceived as the same. First, to ascertain the hue-shift values for the whole hue angle, 24 color patches are created with the same lightness and equally spaced inside the hue angle. Then, for the matching experiment, high and normal-luminance displays are characterized for accurate color reproduction and placed in a dark room. Next, the patches are displayed one-by-one on both displays, and the hue value on the high-luminance display adjusted by observers until the hue values of the patches on both displays appear the same visually. This colorimetric hue difference between the two patches after adjustment is called the hue-shift value. The experiment is recursively performed for all patches, resulting in a hue-shift value for each patch. These hue-shift values are then approximately fit piecewise into seven sinusoidal curves, which are seven functions of the hue value, to enable a hue-shift amount to be calculated for an arbitrary hue value. The hue correction using the hue-shift-model functions is performed in CIELAB LCh color space, where an input RGB image is converted to CIELAB color space, then the hue-shift value that is the input for the hue-shift-model functions for each pixel is calculated. As a result, the hue value for each pixel in the image is shifted by the amount calculated by the hue-shift-model functions. Finally, the hue-corrected image is inversely converted to the output RGB image. To confirm the effectiveness of the proposed hue-shift model, it was applied to several test images on a high-luminance display, and a z-score comparison performed using a visual matching experiment.

2. MATCHING EXPERIMENT FOR QUANTIFICATION OF HUE SHIFT

2.1. Creation of patches

Two displays were prepared, an LZ-10 LCD (431.9cd/m2 as the maximum luminance) and EIZO T966 CRT (114.6cd/m2 as the maximum luminance), where the former was used as the high-luminance display and the latter as the normal-luminance display. Both displays were used with a default setting. To generate accurate colorimetric values, device characterization was performed using an interpolation model for the LCD and the GOG-model for the CRT, and the results were 0.64 and 1.1 as the average color difference, respectively, which are permissible differences.
The patches were created in CIELAB LCh color space to create patches that only varied in terms of the hue value, and not the lightness or chroma. To investigate the hue-shift phenomenon at low, middle, and high levels of lightness, the hue shift was observed at three lightness levels (L=40, 60, 80). The chroma values for each lightness level were also fixed at 22, 25, and 23, respectively, representing the maximum chroma value creating a hue circle inside the display gamut for each lightness level. Twenty four patches were then created for each lightness level, equally spaced inside the hue angle, and the patches displayed on the LCD and CRT displays one-by-one. The luminance of the patch displayed on the LCD was about four times higher than the corresponding patch luminance displayed on the CRT. Figure 1 shows the patches at the three lightness levels in CIELAB color space with a fixed chroma for each lightness level. Meanwhile, Figure 2 shows the chromaticity values

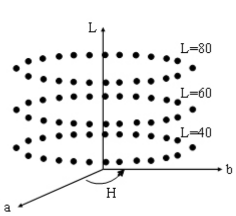
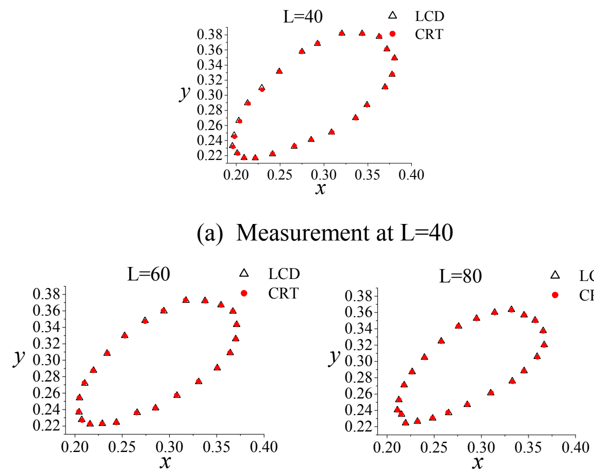


Figure 1. LCD patches generated in CIELAB color space



(a) Measurement at L=40

(b) Measurement at L=60 (c)Measurement at L=80

Figure 2. Measurement of LCD patches and CRT patches at each lightness level

for the patches on the CRT and LCD displays that were measured using a Minolta CS-1000 spectroradiometer. In this figure, the corresponding patches on the two displays had similar chromaticity values. However, the measured luminance for the LCD patches was four times higher than that for the CRT patches; at L=40, the measured luminance for all the patches on the CRT and LCD displays was nearly 10.0cd/m2 and 39.5cd/m2, respectively, at L=60, it was nearly 26.0cd/m2 and 100.5cd/m2, and at L=80, it was nearly 51.0cd/m2 and 201.0cd/m2, respectively.

2.2. Procedure for matching experiments

The matching experiments were performed in a dark room. The two displays were placed on a table side-by-side in front of the subjects. The width and height of the patches on each display were fixed at 1/5 of the LCD display height, i.e. 11cm, while the observation distance was 156cm, representing four times the LCD display height. Figure 3 shows the environment for the color-matching experiments.
The subjects were six men and one woman, with an age range between 26 and 34. All the subjects were researchers on color science and color imaging, and had normal color vision. The subjects were allowed to adapt to the dark room for 10 minutes before the experiment. As shown in Figure 4, the created patches were displayed one-by-one with a different luminance at each lightness level. The subjects first watched the patch on the CRT display for 5 seconds, then watched the patch on the LCD display. Next, the subjects adjusted the hue value of the LCD patch until the patch hues appeared the same on both displays. The hue-shift value for each patch on the LCD was determined based on the hue difference between the two patches before and

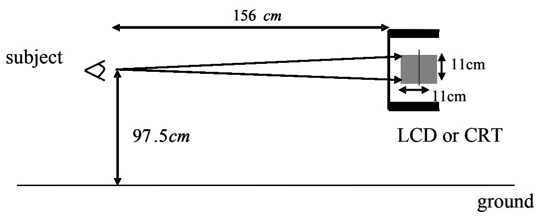


Figure 3. Environment for matching experiments

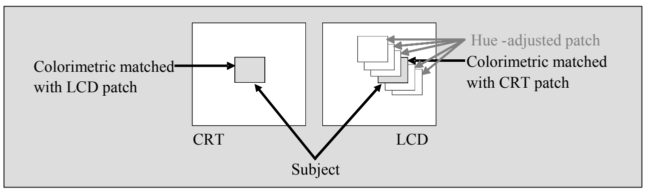


Figure 4. Method for color-matching experiment

after adjustment. The subjects performed the same procedure four times for all patches at the three lightness levels.

2.3 Hue shift results from matching experiment

The hue-shift value is intended to be a single value for each patch based on generalization. However, the hue-shift values for one patch differed from the four iterative experiments. Thus, to determine one hue-shift value for each patch, the average value of the distribution was used. Figure 5 shows the average hue-shift values with a standard deviation for each patch at the three lightness levels. At about 0°~45°, 180°~270°, and 330°~360°, the hue-shift values were positive, whereas, at about 35°~180° and 270°~330°, the hue-shift values were negative. Also, the hue shifts in the blue, red, orange, and yellow regions were dominant.

3. MODELING OF HUE-SHIFT DATA

As shown in Figure 5, the tendency of the hue shift was similar for each lightness level. Although the absolute luminance of the patches on each display differed among the three lightness levels, the luminance ratio between the CRT and the LCD was similar. That is, the hue-shift amount did not depend on the absolute luminance level, but rather on the ratio of the luminance level between the two patches. Also, the small difference in the hue-shift amount among the three lightness levels was considered as an experimental deviation. Thus, the average hue-shift values for the three lightness levels were used as representative hue-shift values that were lightness-independent.
The representative values are shown in Figure 6 as plus symbols. Next, the representative hue-shift values were fitted piecewise into seven sinusoidal functions to enable

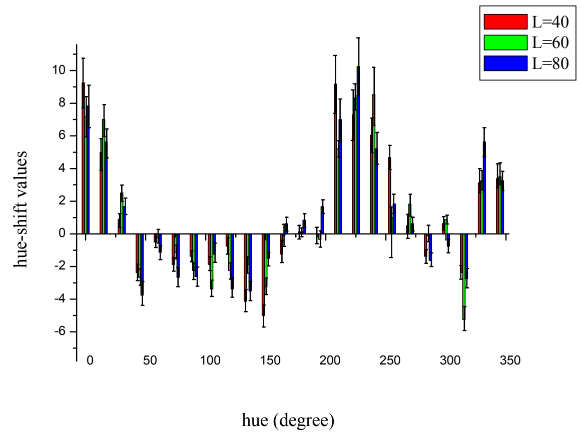


Figure 5. Average quantities of hue-shift values with standard deviation for each patch at three lightness levels

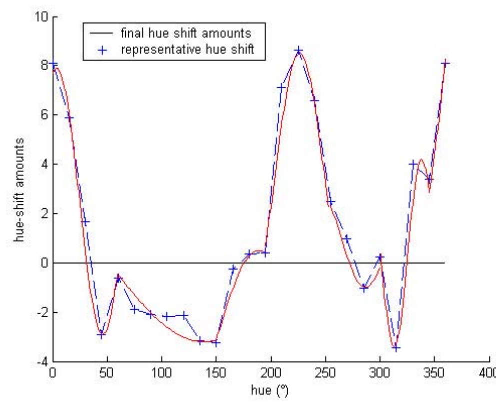


Figure 6. Average value of hue shift for three lightness levels (dotted line) and hue-shift model (straight line)

hue-shift values to be obtained for any arbitrary input hue value. As a result, the hue-shift model using the seven sinusoidal functions is given by Eq (1).

$$\Delta hue_{ab,shift}(h_{ab}) = \begin{cases} 5.4\times\sin(h_{ab}/13.5+1.3)+2.5 & 0 \le h_{ab} \le 60 \\ 3\times\sin(h_{ab}/53+2.1)-0.2 & 60 < h_{ab} \le 150 \\ 3.7\times\sin(h_{ab}/25+0.3)-3.2 & 150 < h_{ab} \le 195 \\ 5\times\sin(h_{ab}/14.5-1.48)+3.5 & 195 < h_{ab} \le 255 \\ 2\times\sin(h_{ab}/14-3.2)+1 & 255 < h_{ab} \le 300 \\ 3.8\times\sin(h_{ab}/8-3)+0.4 & 300 < h_{ab} \le 345 \\ 5.4\times\sin(h_{ab}/13.5-1.3)+7 & 345 < h_{ab} \le 360 \end{cases} \quad (1)$$

4. APPLICATION TO DIPLAY

The hue-shift model was applied as inverse device characterization to modify the arbitrary hue value of each pixel in a high-luminance display. In Figure 7, the input CIEXYZ values for each pixel were converted to CIELAB values, which were then used to calculate the lightness,

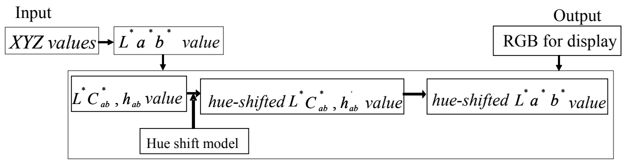


Figure 7. Application of the hue-shift model to display

chroma, and hue. Next, the hue values were adjusted based on the hue-shift model, and CIELAB values inversely calculated from the modified hue values. Finally, the output RGB values after the hue shifting were estimated from the CIELAB values using a 3-D LUT with interpolation.

5. EXPERIMANT AND RESULT

The effectiveness of the proposed model was subjectively verified using various test images. Figure 8 shows the three original images: sky, orange, and red cloth. Figure 9 then shows the hue-corrected images, where the influence of the proposed model turned the sky color purplish, the orange color reddish, and the red color vermilion.

In the experiment, the original images were compared with hue-modified images using the proposed method and Hunt 94u color appearance model. First, the original image was displayed on the CRT, then the original image and hue-modified images based on the proposed method and color appearance model were displayed in turn on the LCD, where the luminance of the three images displayed on the LCD was about four times higher than that of the original image displayed on the CRT. The subjects were then asked to select which of the three images on the LCD visually matched the one displayed on the CRT. This experiment was performed two times with seven subjects. As shown in Figure 10, the experimental results revealed that most subjects selected the LCD images modified using the proposed method as more similar to the images on the CRT.

6. CONCLUSION

The hue-shift phenomenon was modeled and a hue-correction method proposed to provide perceptual matching between high and normal-luminance displays. The value of the hue-shift relative to the hue angle was obtained by matching experiments using patches in CIELAB color space.

(a) Sky (b) Orange (c) Red shirt

Figure 8. Test images on LCD display

(a) Sky (b) Orange (c) Red shirt

Figure 9. Hue-modified images on LCD display

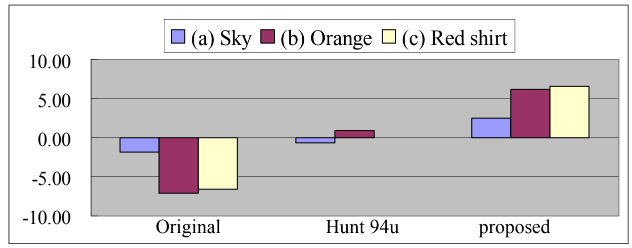


Figure 10. Experimental results

The resulting values were then fitted piecewise into seven sinusoidal functions to enable hue-shift amounts to be determined for arbitrary hue values when using the hue-shift model, thereby allowing the input hue value of each pixel in a high-luminance display to be corrected during inverse characterization. For evaluation, a matching experiment was performed with four test images, and the results confirmed that the proposed images on the high-luminance display appeared closer to those on the normal-luminance display.

6. ACKNOWLEDGMENTS

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7. REFERENCE

[1] M. D. Fairchild, *Color Appearance Models second edition*, John Wiley & Sons, 2005.

[2] Weale, R. A., “When red turns to green,” *Nature*, 201, 661-663, 1964

[3] Vos, J. J., “Are unique and invariant hues coupled?,” *Vision research*, 26, 337-342, 1986

[4] R.W.G Hunt, *Measuring Colour Third edition*, Fountain Press, England, 1998.

[5] Ralph W. Pridmore, "Bezold-Brücke hue-shift as functions of luminance level, luminance ratio, interstimulus interval and adapting white for aperture and object colors," *Vision research*, Turramurra, Sydney, Australia, vol. 39, pp. 3873-3891, 1999.