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Correction of the Hue Shift Phenomenon Due to an Additional White Channel in a DLP Projector

Ho-Gun Ha, Il-Su Park, Wang-Jun Kyung▲, Dae-Chul Kim▲, and Yeong-Ho Ha▲
School of Electronics Engineering, Kyungpook National University, 1370 Sankyuk-dong, Buk-gu, Daegu 702-701, Korea
E-mail: yha@ee.knu.ac.kr

Abstract. *RGB display devices with a white channel have recently been developed to produce a high brightness with low power consumption and enhance the image contrast. However, the addition of a white channel can change the perception of the color represented on the display device because visual adaptations in human are affected by this addition. Although the measured chromaticity coordinates of a color represented with and without a white channel remain the same, the perceived hue is changed. Therefore, this article presents an analysis of the hue shift phenomenon and proposes a hue correction method to provide perceptual color matching between a DLP projector with and without a white channel. To quantify the hue shift phenomenon, color patches are generated at equally spaced hue angles and then individually displayed by a projector and on a CRT monitor. The patches on the CRT monitor are reproduced through device characterization to have an equal colorimetric value with the same patches displayed by the DLP projector with no white channel, so that the patches appearing on the CRT monitor can be used as reference images. Next, the hue for each patch displayed by the DLP projector with a white channel is adjusted by observers until each patch appears the same as its reference image. These adjusted hues are then fitted into three sets of piecewise polynomial functions, which represent the amounts of hue shift required for perceptual color matching. After analyzing the hue shift phenomenon, the RGB for each pixel in the input image of the projector is converted to CIELCh color space to obtain the corresponding hue. This hue is then shifted by the proposed polynomial functions which model the hue shift by adding a white channel. Finally, the corrected hue is inversely converted to RGB in the output image.* © *2013 Society for Imaging Science and Technology.*
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INTRODUCTION

Conventional display represent colors using RGB primaries. Yet, the narrow gamut of such display devices limits their ability to represent natural and vivid colors. Thus, to expand the color representation of conventional three-primary devices, the adoption of an additional color channel has resulted in the recent development of two types of four-primary display devices: RGBY-primary devices including a yellow channel and RGBW-primary devices including a white channel. Enlarging the color gamut with a yellow chromatic channel gives RGBY-primary displays an improved yellow and blue–green color reproduction when compared with conventional RGB-primary displays.[1–4] Meanwhile, adding a white achromatic channel gives RGBW-primary displays a higher brightness with less power consumption and an enhanced image contrast. Digital light processing (DLP) projectors are a typical example of RGBW-primary display devices.

Projectors are now a common display device in offices, schools, and for home theater entertainment. However, when the surround illuminance increases, the projected image becomes dull, appears washed-out, and the contrast is reduced. Thus, to overcome these problems, more light needs to be projected onto the screen, which can be achieved by adding a white channel to a DLP projector that adjusts the white segment of the color wheel. However, when watching a display with an added white channel, the apparent color representation is changed. Although the represented hue of the color is the same as the previous one, it is perceived as a different hue.

The Abney effect is related to the chroma and hue.[5,6] For example, if the color purity around yellow is increased, the appearance of the color changes according to the chroma level. The perceived hue also changes with the color purity, even though the wavelength remains fixed. Abney reported that the perceived hue can be changed by adding white light. Color vision is the ratio of light detected by the three types of cone. By combining the responses of the three types, we are able to perceive any color. Based on this theory, as the response curve of the cone in the psycho-visual system adapts to a stimulus of particular components, the perception of the original color is also adapted to the change of the response curve. However, cone excitation and incident light in the eyes are connected with a nonlinear interaction. Although the absolute values of components in incident light to the eyes are the same, perception is no longer matched. As a result, the psycho-visual system perceives the original color as a different color. The mechanism and phenomenon in hue shift have already been analyzed on the basis of this principle.[7,8]

Accordingly, this article presents a model of the hue shift phenomenon that occurs with a DLP projector that includes a white channel and proposes a correction method based on color-matching experiments. To check the proposed hue shift model, a subjective evaluation is conducted with test images, and the results are expressed in terms of z-scores.[9] The remainder of this article is organized as follows. The second section explains the hue shift effect due to the additional

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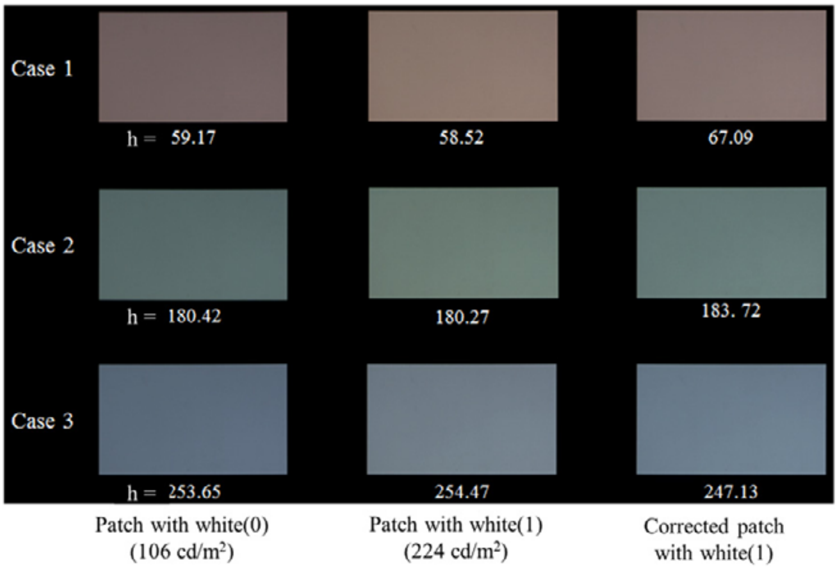

Figure 1. Examples of the hue shift phenomenon due to an additional white channel.

white channel. The third section then describes the proposed method for modeling the hue shift phenomenon and correcting the hue shift. The fourth section presents experimental results, and final conclusions are given in the last section.

THE HUE SHIFT PHENOMENON DUE TO AN ADDITIONAL WHITE CHANNEL

DLP projectors produce a hue shift phenomenon when a white channel is added. While the color of a given patch has the same colorimetric value under identical surround conditions, the psycho-visual system recognizes the color differently. Figure 1 shows three examples of the hue shift phenomenon due to the addition of a white channel. The left column represents patches that do not include a white channel, while the middle column represents patches with a white channel. As shown, the hues of these patches are recognized differently according to the column. Thus, to provide a perceptual match, the hue angles of the patches with a white channel are adjusted manually. As a result, the corrected patches are represented in the right column; these shift by approximately 4°–8° of hue angle and are perceptually similar to the patches without a white channel. In the figure, white(0) means no white channel and white(1) means that a white channel has been added. Since the hue shift phenomenon is caused by adding a white channel, the proposed method estimates the hue shift due to the additional white channel and models it to correct the discrepancy. Figure 2 illustrates how to correct the hue shift due to an additional white channel.

HUE CORRECTION USING THE HUE SHIFT MODEL

To achieve a stable color perception regardless of the addition of a white channel, a hue shift model is proposed through a color-matching experiment. For the color-matching experiment, color patches are generated at equal intervals over the entire range of the hue at a fixed lightness and displayed one by one on the device. The hue for each patch with a white channel is then adjusted to match the corresponding patch without a white channel. The amount of hue shift is determined by adjusting the hue angle, and this procedure is repeated for all the patches. The adjusted hues are then modeled using quartic functions piecewisely, which are used for correcting a hue shift.

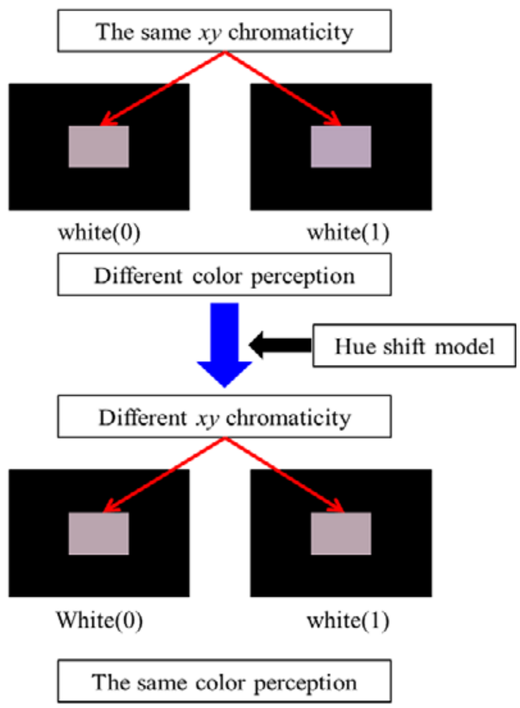

Figure 2. The concept of correcting the hue shift due to an additional white channel.

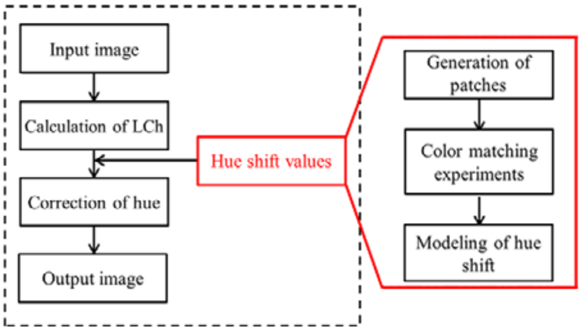

Figure 3. The flow chart of the proposed method.

After modeling the hue shift from the color-matching experiment, the perceptual hue shift of the input image when adding a white channel is corrected. The RGB of the input image is transformed to CIELCh color space and LCh values are calculated for each pixel in the input image. The hue for each pixel is then corrected by using the proposed hue shift model. Finally, the RGB of the output image is calculated using an inverse procedure. Figure 3 shows a flow chart of the proposed method.

Generation of Patches

An LG XGA RD-JT90 DLP projector was used for the experiments. When generating the patches, CIELCh color space was used for a quantitative expression of the hue with unit step. Since lightness, chroma, and hue can be separately treated in CIELCh color space, the hue can be adjusted while keeping the lightness and chroma fixed. Thus, the CIEXYZ values from the DLP projector were transformed into CIEL*a*b* values using the following equations[10]:

$$L^* = 116 \cdot f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500 \cdot f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)$$

$$b^* = 200 \cdot f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right) \tag{1}$$

$$f(t) = \begin{cases} t^{1/3}, & \text{if } t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3}\left(\frac{29}{6}\right)^2 t + \frac{4}{29}, & \text{otherwise} \end{cases}$$

where X_n, Y_n, and Z_n are the tristimulus values of white displayed by the DLP projector. The CIEL*a*b* values were then transformed into CIELCh values, given by the chroma, C, and hue angle, h, of the color

$$C = \sqrt{(a^*)^2 + (b^*)^2}$$

$$h = \tan(b^*/a^*). \tag{2}$$

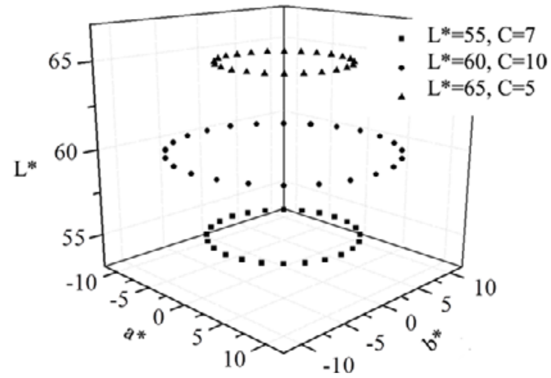

Figure 4. Generation of patches in CIEL* a* b* color space.

The lightness of the generated patches was divided into three levels ($L^* = 55, 60, 65$). For a lightness level below 55, no white channel was added due to the inherent characteristics of the DLP projector. For a lightness level above 65, the hue shift phenomenon is hard to perceive for the human visual system. Since color becomes highly desaturated at a lightness level above 65, a hue shift is difficult to recognize. Thus, the lightness for the color-matching experiment was set at three levels: 55, 60, and 65. Twenty-four patches were generated for each lightness level at 15° intervals. Figure 4 shows the patches generated in CIEL*a*b* color space.

Modeling of the Hue Shift Using Color-Matching Experiments

The color-matching experiment was conducted in a dark room using a DLP projector and a CRT monitor with high color reproducibility. Since DLP projectors show different color reproduction characteristics when adding or not adding a white channel, device characterization of a CRT monitor was used to simulate the same colorimetric values as those displayed by the DLP projector without a white channel.[11–16]

Device characterization was used to estimate device-independent colorimetric values such as CIELXYZ values from the RGB values of the device, which is important to simulate colorimetric values. To verify the accuracy of device characterization, 214 patches were used as test images and mean Δ Eab was calculated. As a result, the mean Δ Eab values of the CRT monitor and DLP projector were 0.5754 and 0.1367, respectively. These figures show a relatively high accuracy of device characterization and enable us to conduct the color-matching experiment.

As such, the patches represented on the CRT monitor and displayed by the DLP projector with a white channel were regarded as the reference image and the projected image to be adjusted, respectively. In this experiment, the reference image on the CRT monitor and the projected image were positioned parallel to the observer's visual field. The observation distance was set as four times the height of the display, while the size of a square patch was 1/5 of the display height. Thus, a patch occupied a visual field of 2° relative to the observer. The background of the CRT monitor was covered with black cloth to prevent the display

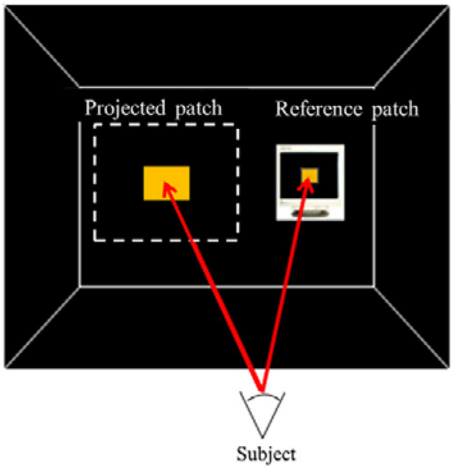

Figure 5. The experimental environment for color matching.

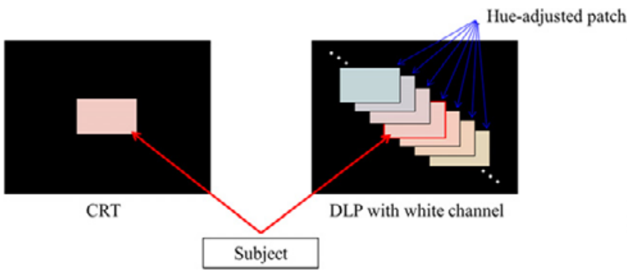

Figure 6. The color-matching experiment.

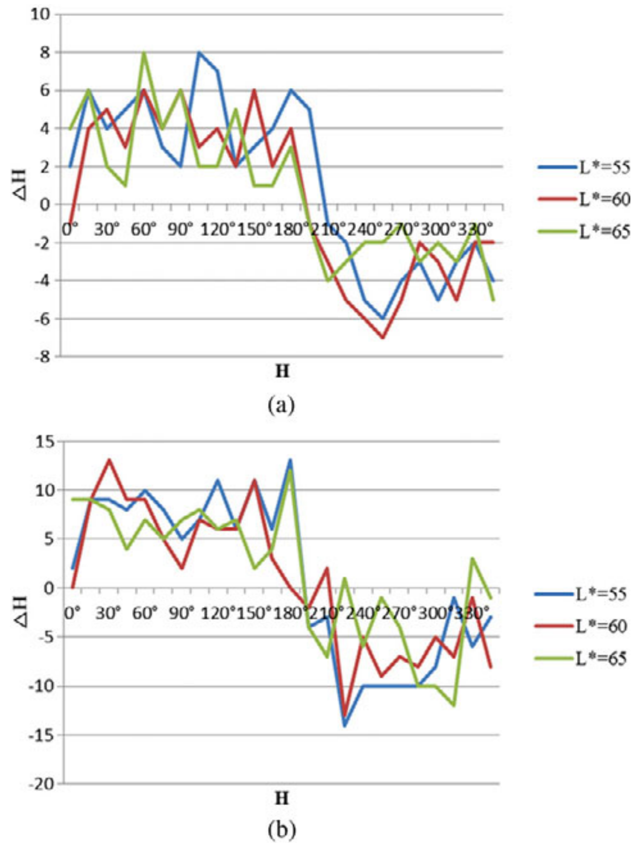

Figure 7. The results of hue shift according to the added white channel; (a) white(0.5) and (b) white(1).

background from influencing the experiment. Figure 5 shows the experimental setup and environment.

The experiment was conducted using 10 observers, who were given 5 min to become acclimated to the experimental environment. First, the patches were presented on the DLP projector without a white channel, and measured using the CS-1000. Utilizing the measured values for the patches, a reference image was then reproduced for the corresponding CIE XYZ values. A reference image with the same colorimetric values as those displayed by the DLP projector without a white channel was then reproduced on the CRT monitor.

In the next experimental step, the hue displayed by the DLP projector with a white channel was adjusted to match the hue of the reference image. After looking at the patch on the CRT monitor, the observer looked at the same patch displayed by the DLP projector with a white channel. The observer then decided whether the two colors appeared to be the same or not. If the two colors appeared different, the hue of the projected patch was adjusted to the point at which the projected patch and CRT patch appeared to be the same. The amount of hue shift was determined by the angle difference in the hue before and after adjustment. This is shown in Figure 6, which illustrates the color-matching experiment.

The results of the color-matching experiment, given in Table I, represent the amount of hue shift for the same perception at a fixed lightness. The uppermost row in the table indicates the hue angle of the patch in degrees. The leftmost column represents the observers in the experiments. In the table, the numbers indicate the amount of hue shift, while the symbols + and − express the direction of the hue shift. The bottom row of the table shows the mean of the hue shift based on 10 observers, which became the raw data for modeling a function of the hue shift.

To analyze the hue shift according to the added white channel, the color-matching experiment was repeated after setting the added white channel as white(0.5), which means that the white channel is added in about half of the white(1). Both results are shown in Figure 7. Here, it is shown that the variation of hue shift through overall hue angles has a similar tendency regardless of the amount of added white channel. While a positive hue shift is necessary for hue angles between approximately 0° and 200°, a negative hue shift is necessary for the remaining hue angles. This means that yellow and green require positive shifts, while blue requires a negative shift to achieve the same perception. Although the amount of hue shift according to the added white cannot be modeled as a single function, a similar tendency in the hue shift phenomenon is found.

After obtaining the amounts of hue shift from the color-matching experiment with the white(1), these values were piecewisely fitted into polynomial functions for approximately determining the hue shift for an arbitrary hue for each

Table I. The results of the hue shift.

(a) $L^* = 55$

	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°
1	+1	+8	+8	+9	+8	+9	+3	+5	+14	+4	+9	+7
2	+2	+9	+9	+8	+10	+8	+5	+7	+11	+6	+11	+6
3	+2	+10	+12	+7	+9	+8	+5	+9	+8	+7	+12	+9
4	+3	+11	+11	+7	+13	+7	+6	+9	+11	+9	+12	+7
5	+3	+8	+12	+8	+9	+6	+6	+3	+9	+9	+12	+5
6	+1	+9	+8	+9	+10	+9	+3	+7	+12	+7	+8	+6
7	+2	+8	+9	+8	+10	+9	+5	+7	+11	+6	+11	+7
8	+2	+8	+7	+9	+9	+8	+5	+9	+10	+5	+12	+8
9	+3	+11	+8	+7	+11	+7	+7	+11	+11	+8	+10	+7
10	+1	+8	+7	+8	+10	+7	+6	+3	+10	+7	+12	+7
Mean	+2	+9	+9.1	+8	+9.9	+7.8	+5.1	+7	+10.7	+6.8	+10.9	+6.9

	180°	195°	210°	225°	240°	255°	270°	285°	300°	315°	330°	345°
1	+12	+8	−3	0	−14	−7	−12	−9	−6	−1	−5	−7
2	+13	+6	−4	−3	−15	−10	−8	−10	−8	−1	−6	−3
3	+14	+7	−6	−4	−12	−11	−12	−8	−6	+2	−8	0
4	+10	+3	−2	−2	−11	−12	−11	−13	−8	−3	−4	−6
5	+15	+5	−4	−2	−16	−8	−9	−8	−10	−3	−7	+2
6	+14	+5	−3	−1	−12	−9	−11	−9	−7	−1	−7	−7
7	+12	+6	−5	−3	−13	−9	−9	−10	−8	−1	−5	−3
8	+13	+7	−5	−3	−12	−11	−10	−8	−7	0	−8	+1
9	+13	+4	−3	−2	−11	−10	−11	−13	−8	−2	−5	−4
10	+12	+7	−4	−2	−14	−10	−9	−8	−9	−2	−7	2
Mean	+12.8	+5.8	−3.9	−2.2	−13	−9.7	−10.2	−9.6	−7.7	−1.2	−6.2	−2.5

(b) $L^* = 60$

	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°
1	−1	+5	+12	+7	+7	+2	−2	+4	+3	+5	+11	0
2	0	+9	+13	+9	+10	+7	+2	+10	+7	+9	+7	+3
3	+2	+12	+12	+12	+12	+7	+3	+6	+8	+7	+11	+4
4	+1	+11	+15	+10	+6	+6	+2	+7	+8	+7	+11	+4
5	−3	+10	+13	+6	+7	+2	+3	+11	+8	+5	+11	0
6	−1	+6	+11	+12	+12	+7	−2	+4	+8	+5	+7	+3
7	0	+9	+13	+8	+6	+6	+3	+6	+6	+6	+11	+3
8	+2	+11	+13	+9	+9	+5	+2	+7	+3	+5	+13	+5
9	+1	+9	+15	+10	+10	+7	+2	+10	+7	+9	+13	+5
10	−3	+10	+11	+7	+9	+5	+3	+11	+6	+6	+11	+3
Mean	−0.2	+9.2	+12.8	+9	+8.8	+5.4	+1.6	+7.6	+6.4	+6.4	+10.6	+3

	180°	195°	210°	225°	240°	255°	270°	285°	300°	315°	330°	345°
1	+3	−2	+2	−11	−3	−11	−8	−11	−6	−5	−1	−5
2	−4	0	+3	−15	−5	−7	−6	−8	−5	−7	+2	−7
3	+2	−1	+2	−11	−5	−12	−6	−11	−6	−5	+2	−7

Table I. *(continued)*

(b) $L^* = 60$

	180°	195°	210°	225°	240°	255°	270°	285°	300°	315°	330°	345°
4	+2	−3	+3	−15	−5	−9	−6	−7	−4	−9	−1	−8
5	+3	−3	+3	−14	−4	−8	−10	−6	−4	−7	−3	−10
6	−4	0	+3	−12	−7	−12	−6	−7	−5	−5	−2	−10
7	0	−4	−2	−11	−3	−8	−10	−6	−4	−7	−1	−8
8	−2	−1	+2	−11	−5	−11	−7	−10	−5	−5	−1	−5
9	−2	−2	+2	−12	−7	−9	−7	−8	−4	−9	−2	−10
10	0	−4	−2	−14	−4	−7	−8	−10	−5	−7	−3	−10
Mean	−0.2	−2	1.6	−12.6	−4.8	−9.4	−7.4	−8.4	−4.8	−6.6	−1	−8

(c) $L^* = 65$

	0°	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°
1	+6	+12	+9	+3	+7	+5	+7	+8	+6	+6	+2	+5
2	+9	+9	+8	+4	+5	+6	+7	+9	+11	+11	+1	+4
3	+10	+10	+10	+4	+9	+4	+9	+12	+8	+10	+4	+2
4	+9	+9	+10	+4	+9	+4	+8	+9	+11	+6	+1	+3
5	+9	+9	+8	+4	+7	+5	+10	+8	+8	+10	−1	+3
6	+10	+7	+7	+2	+6	+4	+9	+12	+4	+5	−1	+2
7	+10	+10	+7	+2	+5	+6	+10	+8	+6	+7	−2	+4
8	+6	+12	+7	+5	+7	+7	+5	+8	+3	+7	+4	+5
9	+9	+9	+9	+3	+6	+4	+8	+5	+3	+11	+3	+4
10	+10	+7	+7	+5	+7	+7	+5	+5	+4	+5	+3	+4
Mean	+8.8	+9.4	+8.2	+3.6	+6.8	+5.2	+7.8	+8.4	+6.4	+7.8	+1.8	+3.6

	180°	195°	210°	225°	240°	255°	270°	285°	300°	315°	330°	345°
1	+13	−4	−7	0	−4	−4	−3	−13	−11	−13	+1	−3
2	+14	−6	−5	0	−11	−2	−5	−10	−10	−12	+3	−1
3	+9	−4	−5	+3	−9	−2	−5	−7	−8	−11	+2	+3
4	+9	−5	−6	−1	−7	+1	−3	−11	−11	−12	+3	+3
5	+13	+1	−6	+2	−6	−1	−4	−7	−8	−8	+4	0
6	+12	−5	−7	+3	−4	−4	−2	−7	−9	−13	+1	−3
7	+12	−4	−7	+1	−7	+1	−4	−13	−11	−9	+4	−1
8	+12	−4	−7	+2	−9	+2	−4	−11	−11	−11	+2	0
9	+14	−6	−8	−1	−11	+2	−4	−10	−10	−9	+4	+2
10	+12	+1	−8	+1	−6	−1	−2	−7	−9	−8	+4	+2
Mean	+12	−3.6	−6.6	+1	−7.4	−0.8	−3.6	−9.6	−9.8	−10.6	+2.8	+0.2

pixel displayed by the DLP projector with a white channel. To implement the hue shift model as an approximation formula, all hue angles were divided into six parts, representing an interval of 60°, and fitted using a fourth-order polynomial function, as shown in Eq. (3). Table II presents the estimated polynomial coefficients, while Figure 8 shows the hue shift model piecewisely fitted into the fourth-order polynomial functions. The amount of hue shift, Δh_{shift}, is given by

$$\Delta h_{\text{shift}}(x) = P_1 x^4 + P_2 x^3 + P_3 x^2 + P_4 x + P_5 \qquad (3)$$

where the P_i are the polynomial coefficients of the hue shift model.

Table II. Estimated polynomial coefficients of the hue shift model.

(a) $L^* = 55$	P_1	P_2	P_3	P_4	P_5
0–60	0.00000	0.00039	−0.03106	0.84833	2.00000
60–120	−0.00001	0.00243	−0.32431	18.4933	−371.700
120–180	0.00003	−0.01679	3.74346	−368.435	13514.9
180–240	−0.00003	0.02603	−8.09074	1112.76	−57116.2
240–300	0.00000	0.00430	−1.79069	330.285	−22798.2
300–360	−0.00002	0.03083	−15.3877	3407.46	−282486
(b) $L^* = 60$	P_1	P_2	P_3	P_4	P_5
0–60	0.00001	−0.00101	0.01633	0.57444	−0.20000
60–120	−0.00002	0.00789	−1.01585	56.4844	−1137.60
120–180	0.00003	−0.01590	3.54337	−347.903	12703.6
180–240	0.00005	−0.04315	13.4106	−1845.51	94882.4
240–300	0.00001	−0.01534	6.22215	−1120.00	75467.2
300–360	0.00004	−0.05131	25.2730	−5524.07	452112
(c) $L^* = 65$	P_1	P_2	P_3	P_4	P_5
0–60	0.00001	−0.00103	0.02563	−0.14889	8.80000
60–120	0.00000	−0.00183	0.26385	−16.3889	375.200
120–180	−0.00001	0.00844	−1.95741	199.227	−7507.20
180–240	−0.00002	0.01630	−4.88433	645.106	−31669.0
240–300	0.00000	−0.00211	0.69637	−95.6178	4402.20
300–360	0.00005	−0.06243	30.8956	−6784.40	557773

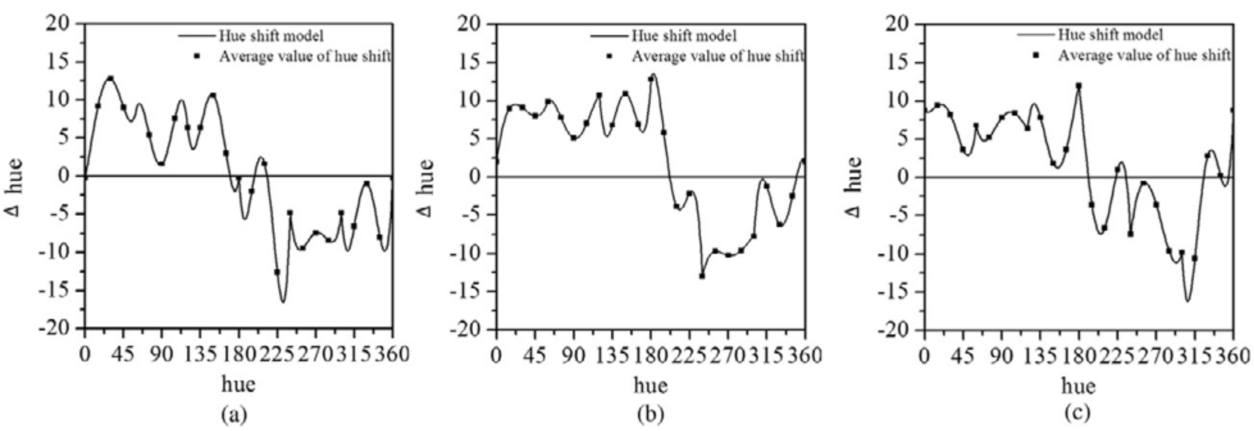

Figure 8. Piecewisely fitted fourth-order polynomial functions of the hue shift: (a) $L^* = 55$, (b) $L^* = 60$, and (c) $L^* = 65$.

Hue Correction in the DLP Projector

The correction of perceptual hue shift represented in the DLP projector by adding a white channel is based on both 3D-lookup table and the hue shift model. Basically, 3D-LUT transforms the RGB values of the input image into CIEL*a*b* values, which are also used to predict the corrected RGB values for the output image of the DLP projector.

First, the RGB values of the input image are transformed into CIEL*a*b* values by using 3D-LUT. Sequentially, the CIEL*a*b* values of the input image are transformed into LCh values. The amounts of hue shift are estimated from the hue shift model which is a fourth-order polynomial function. Then, the hues are corrected, while the lightness and chroma values remain fixed. Finally, the corrected RGB values for the

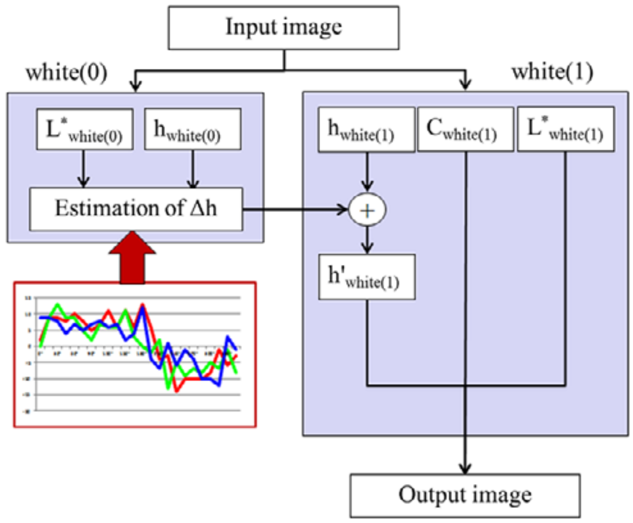

Figure 9. The process of hue correction.

output image of the DLP projector are then calculated using an inverse transform of LCh to L*a*b* and inverse 3D-LUT. Figure 9 shows the hue correction process by using the hue shift model.

EXPERIMENTAL RESULTS AND DISCUSSION

For subjective evaluation, preference test and z-score were employed. The environment of subjective evaluation was similar to the color-matching experiment. The DLP projector and CRT were positioned side by side. The observation distance was set as four times the height of the display. A test image displayed by the DLP projector without a white channel was reproduced on a CRT monitor as the reference image. Two resulting images were reproduced in turn, where one was the corrected image by using CIECAM02, while the other was the corrected image by using the proposed hue shift model.[10,17,18] Then, one of the two images, which was similar to the reference image, was selected. In the subjective evaluation, a total of seven test images were used for evaluation, as shown in Figure 10, and ten observers participated in the evaluation.

Figure 11 represents the reference images and resulting images. The first and second columns in Fig. 11 represent the reference images without and with a white channel, respectively. When comparing two images, the hue shift in some parts of the reference image with a white channel can be easily recognized. It is especially distinguishable around magenta and blue. These parts definitely require hue correction to achieve the same perception. The tendency in hue shift as seen in the test images is also similar to the results of the color-matching experiments. Thus, the perceptual hue shift of the DLP projector with a white channel can be corrected by applying the proposed hue shift model.

The third column represents corrected images by using CIECAM02, while the last column represents corrected images by using the proposed method. When the resulting images from the proposed method are compared with ones from CIECAM02, the corrected images by using the hue shift model are closer to the reference images than the other resulting images. About 3° to 12° of hue angle is adjusted in the reference images by the proposed hue shift model. For example, the hue angle of the red bricks beside the pool in Fig. 11(b), which was 337°, is adjusted to 332°. The hue of the sky in Fig. 11(c) is also adjusted by shifting 6°.

Table III shows the results of the observer preference test for each image, while the z-scores are presented in Table IV. As shown, the z-score values for the proposed method are generally higher, indicating that the images corrected using the hue shift model are closer to the reference images.

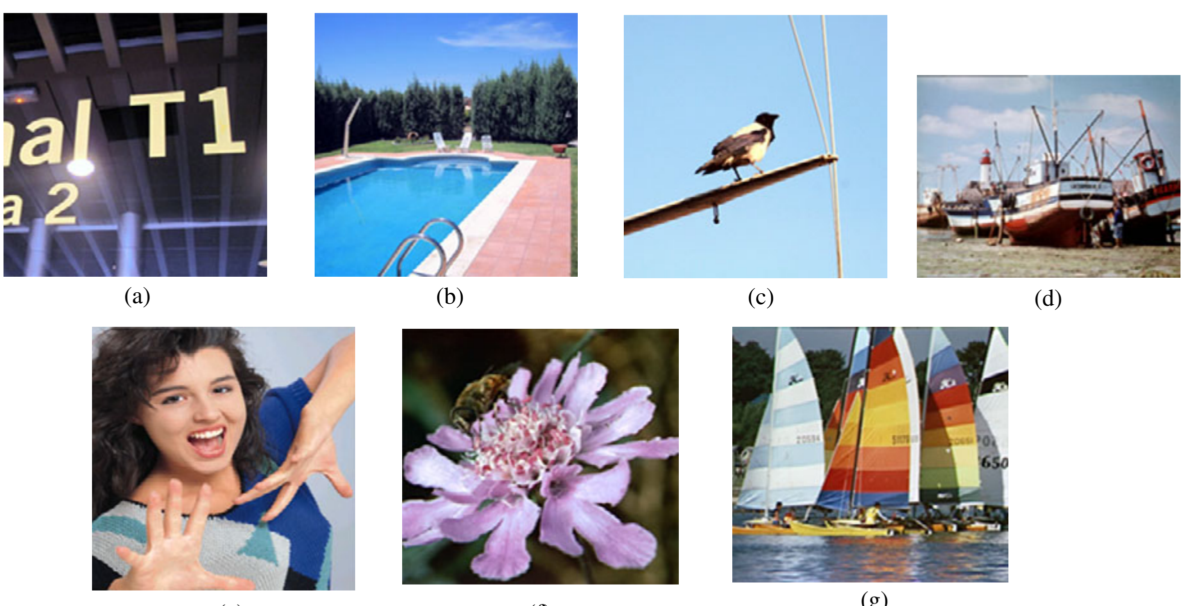

Figure 10. Test images in the experiment: (a) terminal, (b) pool, (c) bird, (d) boat 1, (e) woman, (f) flower, and (g) boat 2.

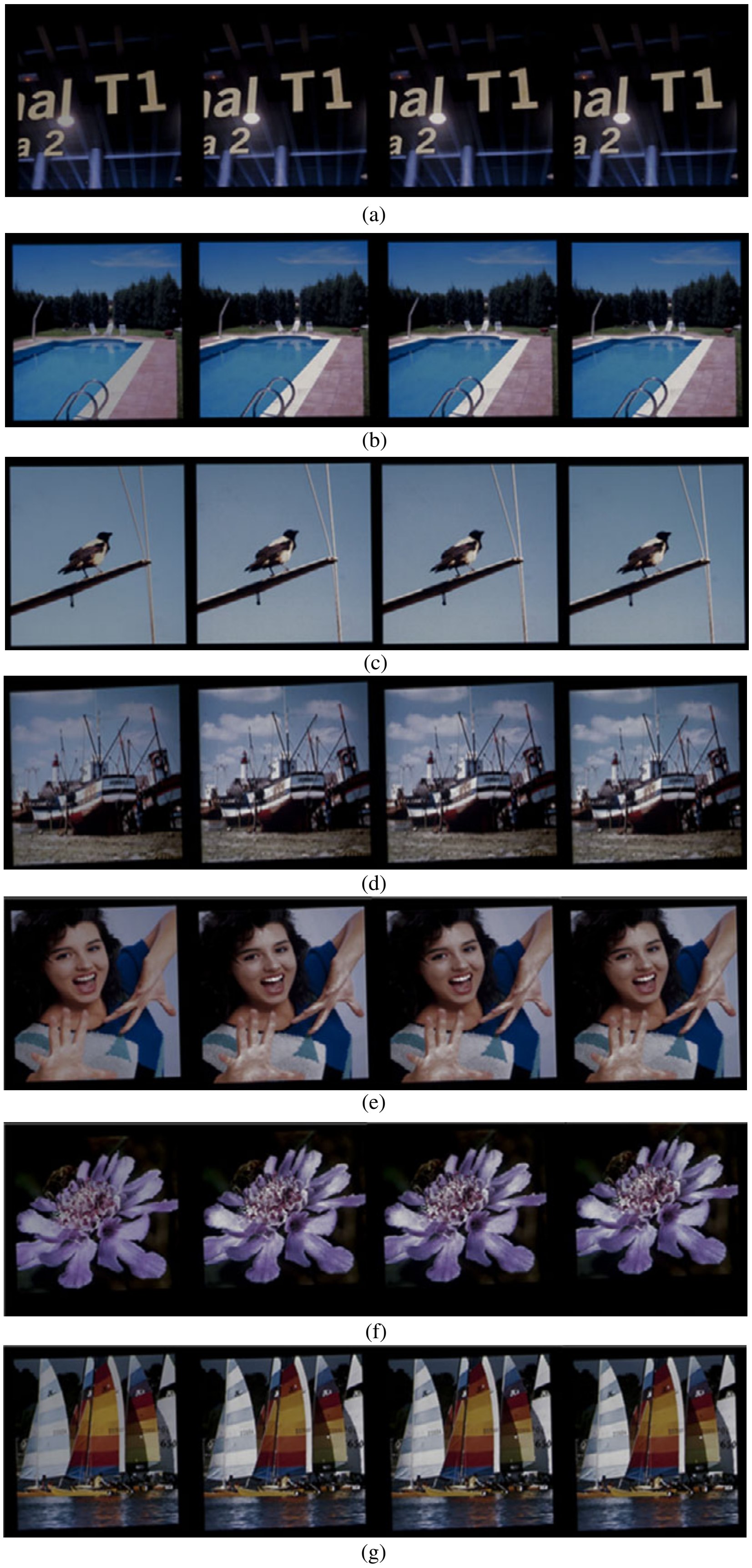

Figure 11. Reference and resulting images in the experiment: (a) terminal, (b) pool, (c) bird, (d) boat 1, (e) woman, (f) flower, and (g) boat 2.

Table III. The results of the observer preference test.

	(a)	(b)	(c)	(d)	(e)	(f)	(g)
CIECAM02	3	2	1	2	1	3	2
The proposed method	7	8	9	8	9	7	8

Table IV. The results of z-score.

	(a)	(b)	(c)	(d)	(e)	(f)	(g)
CIECAM02	−0.52	−0.84	−1.28	−0.84	−1.28	−0.52	−0.84
The proposed method	0.52	0.84	1.28	0.84	1.28	0.52	0.84

CONCLUSIONS AND DISCUSSION

This article analyzed the hue shift phenomenon caused by adding a white channel and suggested a hue shift correction method in a DLP projector. To solve the altered hue perception of humans when adding a white channel, the hue shift between with and without a white channel is quantitatively analyzed from color-matching experiments. The experiments are conducted using patches created in CIELCh color space with and without a white channel, and the amounts of hue shift are modeled. Finally, a corrected image is obtained using the hue shift model that is piecewisely fitted into fourth-order polynomial functions. Experiments confirm that the images obtained using the proposed method look similar to the reference images. In addition, the proposed hue shift model is represented in device-independent color space such as CIELCh. Thus, the proposed method can also be applicable to any device with an added white channel if device characterization is accomplished well.

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