Color Appearance Control for Color Vision Deficiency by Projector-Camera System

Yoshiki Koshikizawa, Takahiko Horiuchi and Shoji Tominaga
Graduate School of Advanced Integration Science, Chiba University, Chiba, Japan

Abstract

*Color vision deficiency is the decreased ability to perceive color differences. To overcome this deficiency, supporting techniques for realizing barrier-free color environments are required. This paper proposes a color appearance control system to enable people afflicted with color vision deficiency to easily distinguish between confusing colors on any printed images using a projector-camera system. The proposed system captures a printed image using a video camera and shifts the lightness components of each pixel by super-imposing a compensation image obtained from the projector device onto the printed image. The compensation image is produced in the CIEL*a*b* color space for iteratively adjusting the desired lightness components toward the target lightness. The feasibility of the proposed system is verified experimentally using real printed images.*

Introduction

There are inter-individual differences in color perception. Human eye has cone cells that generate an electrophysiological response to light. Cone cells are divided into three types based on their different spectral sensitivities: long-wavelength sensitive cones, middle-wavelength sensitive cones, and short-wavelength sensitive cones. The inter-individual differences in color vision come from a lack of these three cone cells or from a shift in their spectral peak. These differences create a condition called color vision deficiency.

In everyday life, we acquire a variety of information from colored designs such as route maps, advertisements, and sign boards. However, these colorful designs are made for normal color viewers, and color vision deficiency is rarely considered during their creation; hence, a person having color vision deficiency will have a difficulty in distinguishing the combination of certain colors. Figure 1 shows a route map of the Tokyo subway, where the difference in colors simulates the differences in appearance between normal trichromatic and dichromatic vision. A dichromat may confuse different routes painted in different colors, as shown in Fig. 1(b). According to Ref. [1], 7.4% of European males, 4.2% of Asian males, and 2.6% of African males have a red-green color vision deficiency. Therefore, this problem has become a serious social issue.

Recently, a new design concept, the so-called *universal design*, was developed to solve the problem of selecting color combinations, letter fonts and graphical schemes that can be discriminated by individuals with various vision deficiencies [2],[3]. The present state of color design which based on this new concept is limited to designs in which a small number of different colors are used, such as in an Ishihara test chart. Such a design is not always based on color theory and is also not automatic.

This paper proposes an appearance control system that uses a projector-camera system for individuals with different types of vision deficiency. Thus far, projector-camera systems have been developed as adaptive projection systems for various applications such as appearance control [4], geometrical compensation [5],[6], feature tracking [7], and gamut extension [8]. There have been a couple of reports on their use in color vision deficiency. Yamashita [9] proposed a method for projecting border lines on object surfaces and painting in visible shades of confusing colors. Amano [10] proposed an interesting technique for enhancing the appearance of color images using Jefferson's method [11]. However, these conventional approaches were verified using only simply designed materials with a few painted colors, and were not verified for natural images having many colors. Furthermore, these approaches were tested only for people with disabilities and not for those with normal color vision. From a practical point of view, a compensation technique should be useful for both, that is, the color appearance of the image compensated by the projection should be natural to all viewers.

(a) Trichromatic vision *(b) Dichromatic vision*
Figure 1 Example of differences in color vision.

In this paper a projector-camera system with a dynamic feedback control is proposed for improving the color appearance for individuals with different types of vision deficiency. The proposed system captures a printed image using a video camera, and shifts the lightness components of each pixel by super-imposing a compensation image obtained from the projector device onto the printed image. By shifting only the lightness component of the printed image, our system can facilitate the distinguishing between confusing colors and produce the more natural colors of the captured target image printed on white paper, not only for viewers with color vision deficiency but also for viewers without such a deficiency. The color appearance of an image printed on a reflective object is then compensated using this system.

Overview of Color Vision Deficiency

The average human retina contains two kinds of light cells: rod cells and cone cells. Normally, there are three kinds of cones, each containing a different pigment, which are activated when the pigments absorb light. The spectral sensitivities of the cones differ: one is maximally sensitive to short wavelengths (S), one to medium wavelengths (M), and the third to long wavelengths (L); the peak sensitivities of these cones are in the blue, yellowish-green, and yellow regions of the spectrum, respectively.

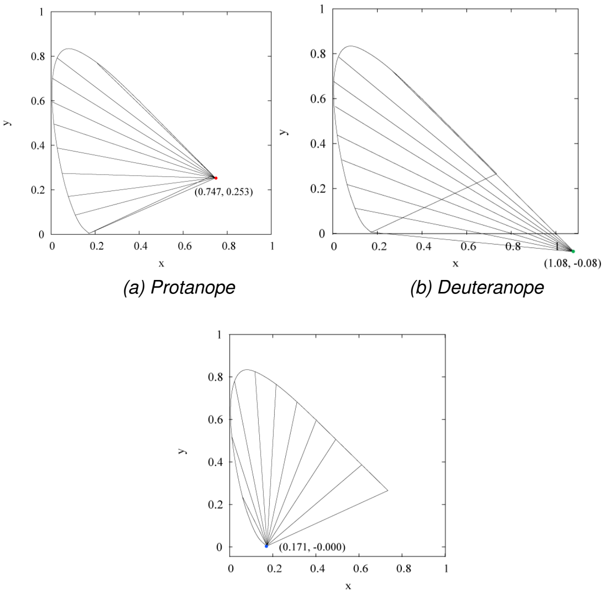
Color vision deficiency is caused by a fault in the development of either or both sets of retinal cones that generate an electrophysiological response to light and transmit that information to the optic nerves. Generally, color vision deficiency can be classified into three types: anomalous trichromacy, dichromacy and monochromacy. Anomalous trichromacy comes from a shift of the spectral peak sensitivity of one of the cones. It is also classified into three types, protanomaly, deuteranomaly, and tritanomaly, depending on a shift of spectral peak sensitivity in the L-cone, M-cone, or S-cone, respectively. Dichromacy is a severe form of color vision deficiency caused by a lack of one of the cones, and is classified into three types, namely, protanope, deuteranope, and tritanope, depending on a lack of L-cone, M-cone, or S-cone, respectively. Monochromacy is also a severe form of color vision deficiency caused by a lack of two or all three cones. Anomalous trichromacy is much more common than dichromacy. However, since dichromacy is a more severe form of color vision deficiency, we focus on dichromacy in this paper.

Dichromacy makes it difficult to distinguish between specific colors. A protanope or deuteranope has difficulty in discriminating between red and green, while a tritanope has difficulty in discriminating between yellow and blue. Such viewers cannot distinguish between two homogeneous lights with equal luminance because they perceive these two homogeneous lights as one homogeneous light owing to a lack of the proper specific cone. Figure 2 shows confusion lines plotted on a CIE1931 x-y chromaticity diagram. Dichromats can match any two colors along a confusion line simply through a brightness adjustment in one of them. As shown in Fig. 2, the confusion lines converge to one point in the chromaticity diagram. This point is called the co-punctal point. Brettel et al. proposed a simulation model [13] for a normal color viewer to note the color as seen by a dichromat. In their algorithm, color stimuli are transformed into the LMS space. Then in LMS space, colors are projected on the plane toward the missing cone axis, and are converted to RGB color space.

Projector–Camera System

Figure 3 shows the system setup of the proposed color appearance control system. A compensation image is displayed on a target image printed on white paper using an EPSON EB-826W projector (8-bit RGB 1280 × 800 resolution), and the target image is captured using an Allied Vision Technologies Pike F-032 camera (8-bit RGB 640 × 480 resolution). The calibration and compensation algorithms run on a Windows OS computer with a 2.0 GHz Celeron CPU. The target printed image is illuminated using D65 artificial daylight lamps.

One of the basic requirements of the projector-camera system is the geometric mapping between points on the projector plane and the corresponding points on the image plane. Note that the projector-camera system can be designed such that the geometric mapping between the displayed and acquired images is fixed. This is achieved by making the optics of the projection and the imaging systems coaxial. Although our system is not exactly coaxial, the camera is placed at the back of the projector to create a coaxial-like condition, as shown in Fig. 3. Hence, the geometric mapping between the camera and projector must be modeled appropriately. We also need a relationship between the projector output and the lightness component. In this section, we explain the calibration algorithms.



(a) Protanope (b) Deuteranope

(c) Tritanope

Figure 2 Confusion lines on an xy chromaticity diagram.

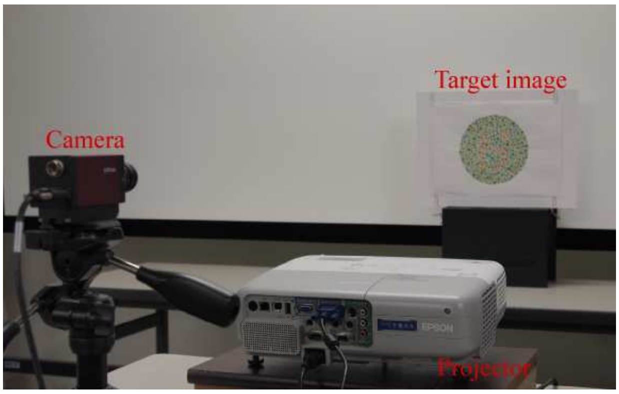
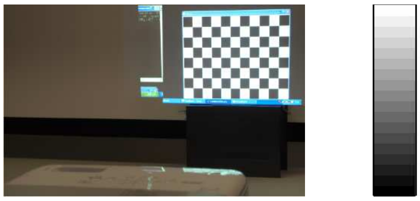


Figure 3 Projector-camera system used for color appearance control.

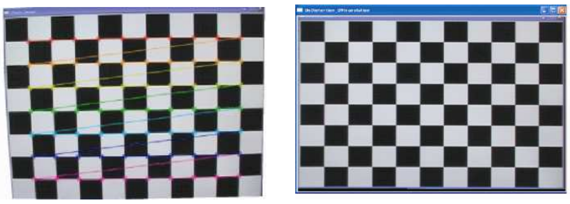
Geometric calibration

To determine the geometric mapping, we use the calibration algorithm proposed by Zhang [12]. This algorithm requires a planar checkerboard grid placed at different orientations in front of the camera. In our system, 18 planar checkerboard patterns with different gray levels of 0 to 255, at intervals of 15, are projected onto a screen. Figure 4 shows the projected patterns used in our calibration. The projected patterns are also used in the lightness calibration. The algorithm extracts the corner points of the checkerboard pattern to compute the projective transformation. Next, the camera's interior and exterior parameters are recovered using a closed-form solution. A final nonlinear minimization of the reprojection error, solved using the Levenberg-Marquardt method, refines all the recovered parameters. After recovering the camera parameters, the camera lens distortions are corrected. Figure 5(a) shows the extracted corner points, and we can confirm that the image is distorted. Figure 5(b) shows the results after a geometric calibration. We can confirm that the lens distortions and the geometry position were corrected.



(a) Projected black calibration pattern (b) 18 gray levels used

Figure 4 Projected patterns used in our calibration.



(a) Extracted corner points (b) Corrected geometry

Figure 5 Geometric calibration process.

Calibration of lightness components

In this paper, we shift the lightness components of the printed image using our projector-camera system. Our system projects a gray compensation image on the printed material. Therefore, the system requires a relationship between the projector output value and the lightness component in the CIEL*a*b* color space. This relationship is realized by obtaining L* from the camera linear RGB value of the captured checkerboard colors.

Assume that the projector and camera have three color channels with 8-bit intensity, which can be described by column vectors **P** and **C** as follows:

$$\mathbf{P} = \begin{bmatrix} R_P & G_P & B_P \end{bmatrix}^T, \quad \mathbf{C} = \begin{bmatrix} R_C & G_C & B_C \end{bmatrix}^T. \tag{1}$$

Let γ_C be the gamma function of the camera devices. Let LUT_p be a transformation using a look-up table of the projector device, which is calculated in advance, for a linear mapping between the projector output and the camera input RGB values. The linear RGB values of both devices can then be expressed as

$$\begin{aligned} \mathbf{P} &= \begin{bmatrix} R_p & G_p & B_p \end{bmatrix}^T \\ &= LUT_p\left(\begin{bmatrix} (R_p/255) & (G_p/255) & (B_p/255) \end{bmatrix}^T\right), \end{aligned} \tag{2}$$

$$\begin{aligned} \mathbf{C} &= \begin{bmatrix} R_c & G_c & B_c \end{bmatrix}^T \\ &= \begin{bmatrix} (R_c/255)^{\gamma_c} & (G_c/255)^{\gamma_c} & (B_c/255)^{\gamma_c} \end{bmatrix}^T. \end{aligned} \tag{3}$$

Linear RGB vector **C** is converted into the CIEXYZ color space as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix}, \tag{4}$$

where **M** represents the 3 × 3 matrix of the RGB-XYZ conversion which is obtained in advance and is converted into the CIEL*a*b* color space from the CIEXYZ color space as follows:

$$L^* = 116 f\left(Y/Y_n\right) - 16, \tag{5}$$

$$a^* = 500\left(f\left(X/X_n\right) - f\left(Y/Y_n\right)\right), \tag{6}$$

$$b^* = 200\left(f\left(Y/Y_n\right) - f\left(Z/Z_n\right)\right), \tag{7}$$

where

$$f(s) = \begin{cases} s^{1/3} & s > 0.008856 \\ 7.78s + 16/116 & \text{otherwise} \end{cases}. \tag{8}$$

Here, (X_n, Y_n, Z_n) represents the reference white, which is derived from the captured value of a white (R = G = B = 1.0) projected image.

We assume that the relationship between the projector output value and the lightness component L* is characterized as

$$L^* = LUT_l\left(\mathbf{P}\right), \tag{9}$$

where LUT_l is a look-up table that obtains L^* from the projector's linear RGB value.

To determine LUT_l, we captured the 18 checkerboard gray values shown in Fig. 4(b) and calculated LUT_l using a linear interpolation between these values.

Color Appearance Control

Outline of the Proposed Algorithm

We show the procedure of the proposed algorithm in Fig. 6. In this algorithm, we designed a desired lightness-shifted image for color vision deficiency from an initial captured image. We then adjusted the compensation image for generating the target camera outputs using a feedback control.

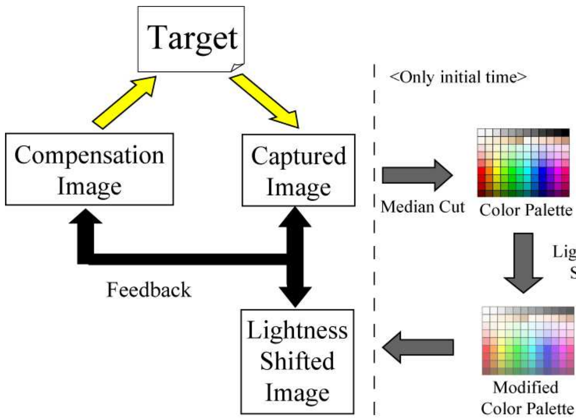


Figure 6 Procedure used for the proposed algorithm.

The color appearance should be controlled to recognize color difference that occurs for color vision deficiency. In addition, the projected compensation image should maintain the color appearance for normal vision, and hence, our system uses an algorithm [14] for shifting the lightness components. This algorithm is based on the amount of difficulty in distinguishing the color difference using a confusion line and the amount of chromatic difference between one color and another. Since our algorithm simply shifts the lightness components, normal color viewers do not perceive a drastic color conversion, but those with a color vision deficiency can distinguish confused colors.

The algorithm has a disadvantage, however, in that it takes a lot of time to calculate the shifted lightness components for all pixels. To solve this problem, we use the median cut algorithm to construct the suitable color palette of an input image and reduce the calculation time using only typical colors.

Appearance Control by Shifting the Lightness Components

To use the lightness shifting algorithm [14], we need to transform the camera RGB values into the CIEL*a*b* values. The transformation between the camera RGB values and the CIEL*a*b* values is calculated from Eqs. (3) through (8). The shifted lightness component $\tilde{l}_i$ of the *i*-th pixel is calculated as follows [14]:

$$\tilde{l}_i = L_i^* + \frac{1}{n}\sum_{i=1}^{n}\delta_{ij}, \quad (10)$$

where $\tilde{l}_i$ represents the shifted lightness component reflecting the color difference in the input image, and L_i^* is the input lightness component of the *i*-th pixel. In addition, *n* is the number of pixels of the input image and δ_{ij} represents the amount of lightness shift considering the difference of colors between *i*-th pixel and *j*-th pixel, and is defined as follow:

$$\delta_{ij} = sign\left(\Delta a_{ij}^*\right) w_{ij}\Phi\left(\Delta C_{ij}^*\right), \quad (11)$$

where Δa_{ij}^* is $a_i^* - a_j^*$. ΔC_{ij}^* is calculated as

$$\Delta C_{ij}^* = \sqrt{\Delta a_{ij}^{*2} + \Delta b_{ij}^{*2}}, \quad (12)$$

where *a** and *b** are components in the CIEL*a*b* color space. The other terms of Eq.(11) are defined as follows:

$$sign(z) = \begin{cases} +1 & z > 0 \\ -1 & \text{otherwise} \end{cases}, \quad (13)$$

$$w_{ij} = \exp\left(-\left(\tilde{d}_{ij}/\beta\right)^2\right), \quad (14)$$

$$\tilde{d}_{ij} = \min\left(d_{ij}, d_{ji}\right), \quad (15)$$

$$\Phi(z) = \alpha z, \quad (16)$$

where α is a parameter used to determine how the algorithm reflects the ΔC_{ij}^* component into the amount of lightness shift, and it is a positive real number. Additionally, w_{ij} is the weight determined by parameters β and d_{ij} based on the amount of difficulty in distinguishing the color difference, and d_{ij} and d_{ji} are the distances between the confusion lines drawn from the co-punctal point to (x_i, y_i) and (x_j, y_j) in the CIE1931 x-y chromaticity diagram. Figure 7 shows an example of distances d_{ij}, and d_{ji} for a protanope. d_{ij} is described as

$$d_{ij} = \left|y_i - ux_i - v\right| / \sqrt{1+u^2}, \quad (17)$$

$$u = \left(y_i - y_{pd}\right) / \left(x_i - x_{pd}\right), \quad (18)$$

$$v = \left(x_i y_{pd} - x_{pd} x_i\right) / \left(x_i - x_{pd}\right), \quad (19)$$

where (x_{pd}, y_{pd}) represents the co-punctal point for a protanope or deuteranope.

This method has the effect of creating a brighter reddish color compared with a greenish color. However, the difference of the lightness between colors becomes small, when color combination of pixels *i* and *j* is dark red and a bright green. Therefore, our compensation is only applied to pixels which satisfy the following condition:

$$\left(L_i^* < L_{ave}^* + \kappa \text{ AND } a_i^* < 0\right) \text{ OR } \left(L_i^* \geq L_{ave}^* + \kappa \text{ AND } a_i^* \geq 0\right), \quad (20)$$

where L_{ave}^* and κ are a lightness average value in an input image and a threshold value, respectively. Symbols "AND" and "OR" mean the logical AND and OR operations. Figure 8 shows the Ishihara test chart applied to this method. We determined three parameters as $\alpha = 0.6$, $\beta = 0.5$ and $\kappa = 10.0$, empirically.

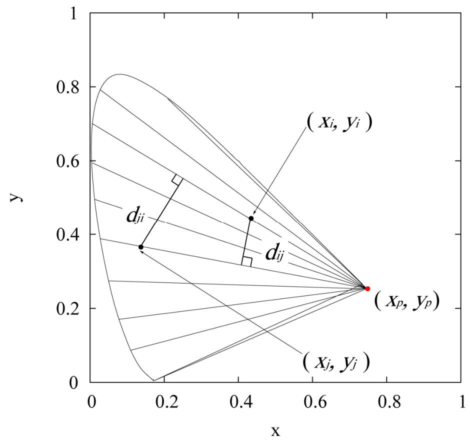


Figure 7 Distance d_{ij} and d_{ji} between the i-th and j-th colors for a protanope.

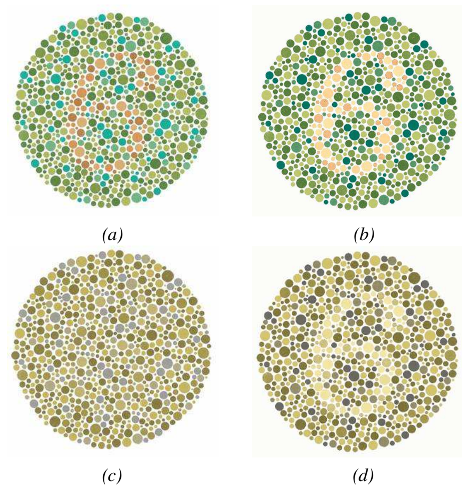


Figure 8 Results of a contrast enhancement for the Ishihara test chart 6: (a) original test chart, (b) modified test chart, (c) protanope simulation of image (a), and (d) protanope simulation of image (b).

Fast Algorithm by Color Palette Selection

To reduce the calculation time, we adopt the median cut algorithm to reduce the number of colors in the input image [15]. The median cut algorithm is a well-known division clustering technique that begins from the minimum RGB box containing all the colors of an input image and divides the longest dimension of the largest RGB box into two smaller boxes so that the two boxes have a roughly equal number of pixels.

In our algorithm, the number of colors of the input image is decreased by applying the median cut algorithm to the input image. After running the median cut algorithm, the obtained colors are changed into a CIEL*a*b* color space from an RGB color space, and the lightness of each color is modified using the above-mentioned contrast enhancement method. Each pixel of the input image is transposed to one color in the color that shifts the lightness components. This fast algorithm runs on a Windows OS computer with a 2.0 GHz Celeron CPU and is applied to the Ishihara test chart (640 × 480 resolution which is the same as the camera resolution). It takes about 2.4 seconds to obtain an image using our fast algorithm. In contrast, it takes about 53,408 seconds to obtain an image using the previous algorithm.

Control Procedure

The control procedure for the proposed algorithm is shown in Fig. 9. The right side of the dotted line shows the processing of the camera color space, while the left side shows the processing of the projector color space.

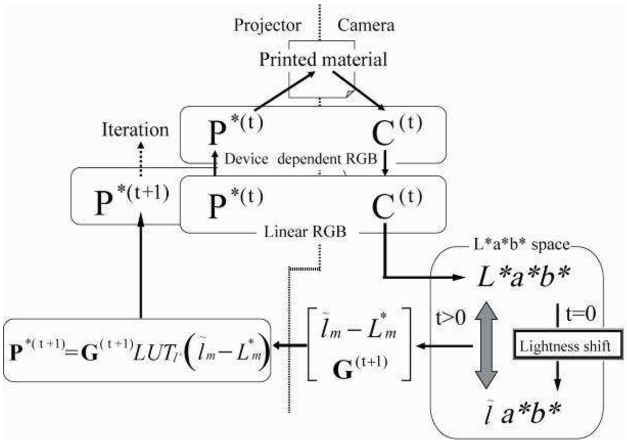


Figure 9 Control procedure for the proposed algorithm.

A control procedure is used in the projector-camera system. Let $\mathbf{P}^{*(t)}$ be a linear 8-bit RGB vector projected onto a printed image at time *t*. For the initial projection, we set a gray image in the linear RGB space as $\mathbf{P}^{*(0)} = [0.5, 0.5, 0.5]^T$. When the RGB intensities of $\mathbf{P}^{*(t)}$ are projected onto the printed image, the color camera captures the reflected intensities as RGB vector $\mathbf{C}^{(t+1)}$ at each pixel. The RGB vector is transformed into linear RGB vector $\mathbf{C}^{(t+1)}$ in the camera color space using Eq.(3).

When $t = 0$, we apply the lightness shift method to a captured image in the camera color space. First, we apply the median cut algorithm to a captured image at time $t = 0$ and reduce the number of RGB colors in the input image. The RGB colors within the regions in Eq.(20) are converted into the CIEXYZ color space. We then convert CIEXYZ values to the CIEL*a*b* color space. At this time we use the CIEXYZ values obtained from the white (R = G = B = 1.0) projection color as the reference white.

In the CIEL*a*b* color space, we modify the lightness component L^* by applying to a contrast enhancement method to the each color, and we then obtain the modified lightness component $\tilde{l}$ from Eq.(10). The gain factors, which are represented by the diagonal elements of matrix $\mathbf{G}^{(t+1)}$, are designed as the ratio between the modified lightness values and the captured lightness values. The feedback gain matrix $\mathbf{G}^{(t+1)}$ is then designed as

$$\mathbf{G}^{(t+1)} = diag\tilde{l} \ \ diag{L^{*(t+1)}}^{-1}. \quad (21)$$

The linear RGB vector $\mathbf{P}^{*(t+1)}$ for the projection at time t +1 is then calculated as

$$\mathbf{P}^{*(t+1)} = \mathbf{G}^{(t+1)} \ LUT_{l'} \left(\tilde{l}_m - L^*_m\right), \quad (22)$$

where *m* indicates the *m*-th color from the number of colors and $LUT_{l'}$ is a look-up table that obtain the projector's linear RGB values from the delta between the modified lightness values and the original lightness values. $LUT_{l'}$ is derived from LUT_l by calculating the delta of the lightness value between the gray projector RGB values and the initial projector RGB values.

As a result, RGB vector $\mathbf{P}^{*(t+1)}$ with 8-bit intensity of the projection at time t + 1 is calculated as

$$\mathbf{P}^{*(t+1)} = 255 * LUT\left(\left[\begin{matrix} R_p^{*(t+1)} & G_p^{*(t+1)} & B_p^{*(t+1)} \end{matrix}\right]^T\right). \quad (23)$$

If any element of $\mathbf{P}^{*(t+1)}$ exceeds the 8 bit-range or if the captured lightness component $L^{*(t+1)}$ fully approaches the modified lightness component $\tilde{l}$, RGB vector $\mathbf{P}^{*(t+1)}$ does not need to be modified and we maintain the previous output of the projector as $\mathbf{P}^{*(t+1)} = \mathbf{P}^{*(t)}$.

Experiments

The feasibility of the proposed system was evaluated experimentally in a darkroom under D65 artificial daylight lamps. The distances between the projector device and a screen, and camera device and screen, were 800 and 1400 mm, respectively, and each square on the projected checkerboard pattern for the calibration was A4 size. The proposed algorithm was implemented on a computer in C++ language. An Ishihara test chart and a subway route map were used as the test samples. To verify the feasibility of the proposed system, we used *Variantor*™ color vision deficiency simulation glasses, which are an experience-based tool to understand what the world looks like to those with a color vision deficiency [16].

The system calibration was first performed by projecting the gray checkerboard pattern shown in Fig. 4. We then investigated any errors in the camera or geometric calibration by superimposing the projected pattern onto a printed checkerboard pattern. As a result, the error in the geometric calibration was less than 2 pixels. It took about 30 s for the calibration. After performing the calibration, we set a printed test sample.

The proposed appearance control algorithm has three parameters α, β and κ. α and β are shifting factors, which are defined in Eqs.(14) and (16), respectively. κ is a threshold value used in the lightness shifting algorithm. In our experiment, we empirically determined these parameters to be $\alpha = 0.5$, $\beta = 0.5$ and $\kappa = 8.0$.

Figure 10 shows the results of the color appearance control for the Ishihara test chart. All images were captured using a digital RGB camera. Figure 10(a) shows a flat-gray uncompensated initial image $\mathbf{P}^{*(0)}$, projected onto the original printed image, while Fig. 10(b) shows a contrast enhanced image created by projecting a compensation image. The compensation images is shown in Fig. 10(c). Figures 10(d) and 10(e) show the pseudo dichromatic views of Figs. 10(a) and (b), which were captured by a digital camera with the simulation glasses placed in front of the camera lens. In Fig. 10(d), we cannot distinguish the number "74" in the Ishihara test chart. As shown in Fig. 10(e), the number "74" is recognized by superimposing the generated compensation image onto the printed image, and the view of after the contrast enhancement is natural for normal color vision. The compensation image with $\mathbf{P}^{*(t)}$ at each pixel was automatically generated by the proposed algorithm iteratively as shown in Fig. 6. In this sample, Fig. 10(b) was obtained after around 6 iterative rounds of processing. During the initial processing, it took about 2.6 seconds to obtain a lightness shift in the image. During the iterative processing, this took about 0.5 seconds.

Figure 11 shows the results for the subway route map test sample. Figures 11(b) through 11(e) show close-up images. We confirmed that the contrast of the specific color appearance was appropriately improved for the natural printed images.

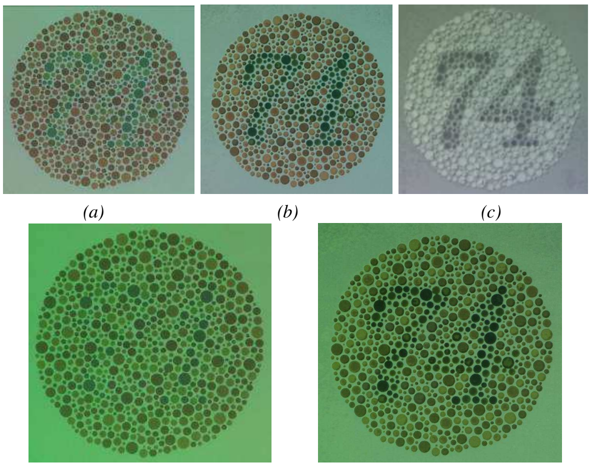


Figure 10 Results of color appearance control for the "74" Ishihara test chart, and a representation of color vision deficiency: (a) before the appearance control, (b) after the appearance control, (c) a compensation image, (d) image (a) viewed through simulation glasses, and (e) image (b) viewed through simulation glasses.

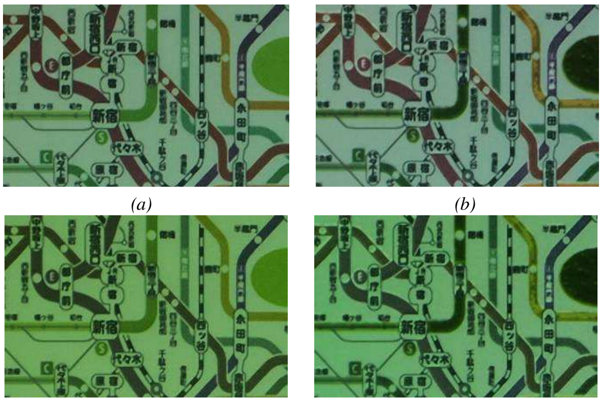


Figure 11 Results of color appearance control for a subway route map and a representation of color vision deficiency: (a) before the appearance control, (b) after the appearance control, (c) image (a) viewed through simulation glasses, and (d) image (b) viewed through simulation glasses.

Conclusions

This paper has proposed an appearance control method for enabling dichromats to easily distinguish confusied colors on any printed images using a projector-camera system. Our system works not only for those with dichromacy but also for normal color viewers, in that the color images maintain their original appearance by shifting only the lightness components. The proposed system was able to capture a printed image with a video camera and shifted the lightness components of each pixel by superimposing a compensation image obtained from the projector device onto the printed image. The feasibility of the proposed method was verified experimentally using real printed images. The control algorithm takes about 2.6 seconds to create a target image, and about 0.5 seconds for iterative processing. A faster and simpler algorithm should be developed as a future study.

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Author Biography

Yoshiki Koshikizawa received his B.E. and M.E. degrees from Chiba University in 2010 and 2012, respectively. His current research interests are color image processing for color vision deficiency.