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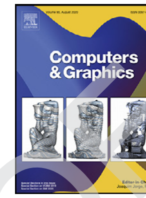

Technical Section

Illusory light: Perceptual appearance control using a projection-induced illusion

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ABSTRACT

With projection mapping, we can control the appearance of real-world objects by adding illumination. A projector can be used to control light reflected from an object, where the reflected light depends not only on the projection but also on the reflectance and environmental light. Because the resulting colors are affected by the reflectance and environmental light, the presentable color range of a projector is limited. The purpose of this work is to broaden this limited range by focusing on the perceived colors. Although our eyes capture reflected light to perceive the colors of an object, the colors perceived by humans are not always the same as the actual colors, and there are often significant differences between them because of the human visual system. To overcome the limitations of a projector based on human perception, we intentionally generate this difference by inducing a visual illusion, namely, color constancy. In this work, we designed an algorithm to determine the projected colors for presenting the desired colors perceptually by employing a color constancy effect. In addition, we conducted a user study and confirmed that our algorithm can (1) create a misperception regarding the color of illumination, (2) broaden the presentable color range of a projector, and (3) shift the perceptual colors in the desirable direction.

1. Introduction

The properties of an object, such as its reflectance, texture, and material, significantly affect its appearance. Projection mapping is a technology that controls the projecting light so that the light reflected on an object surface to appear in a designated color and intensity. It is currently used for entertainment in amusement parks [1], museum events [2], gaming [3], and educational and medical situations [4,5]. Given the degree to which this technology has been adopted, there always be a pressure for further improvement.

A projector can control the appearance of a real-world object by illuminating it, albeit with an upper limit on brightness. Owing to these features and the spectral reflectance of a projected object, only limited colors can be presented by a projector. Environmental light becomes an offset of the projection and decreases the contrast. Thus, the presentable color range depends on “the reflectance of a projected surface” and “the presence of environmental light”. In this paper, we define the “presentable color range” as the range of the colors resulting from projection on an object. Fig. 1 shows how the presentable color range narrows according to these two factors. In Fig. 1-(a), an ideal environment for a projector is shown. When there is no environmental light and the surface is Lambertian, with a reflectance of 1, the projected light reflects off the surface in a completely diffusive manner. Under this situation, the performance of the projector is fully realized. By contrast, when the surface is not white (Fig. 1-(b)), the surface exhibits a biased spectral reflectance. Depending on the spectral reflectance, light with a specified wavelength is barely reflected from the surface. In addition, environmental light, as shown in (Fig. 1-(c)), becomes offset and the contrast of the projection decreases. Under this type of situation, the performance of the projector decreases and the presentable color range narrows.

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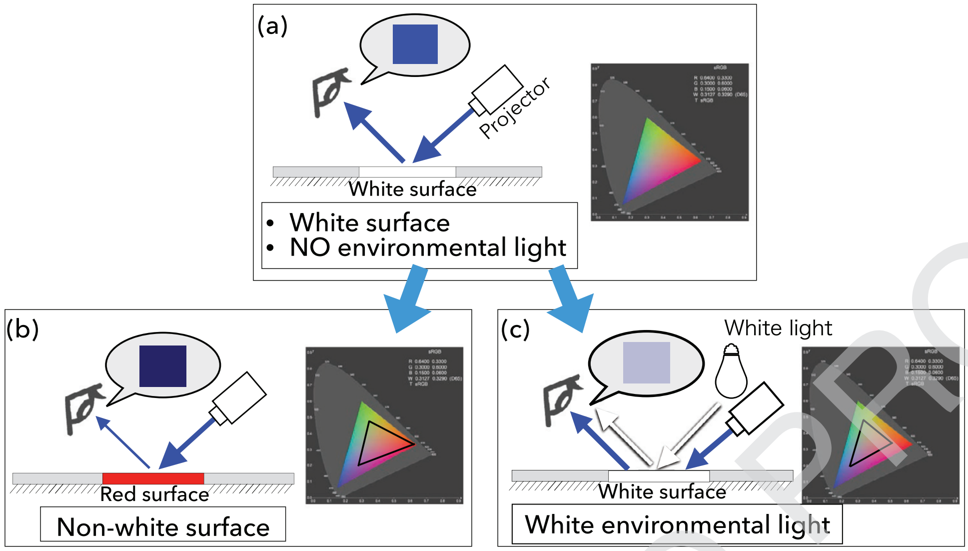

Fig. 1. Presentable color ranges of a projector depending on the surface color and environmental light. (a) Blue illumination from the projector fully reflects on the white surface, (b) the blue illumination hardly reflects on the red surface, and the resulting color darkens, and (c) white environmental light mixes with blue reflected light, and the resulting color becomes more pale. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

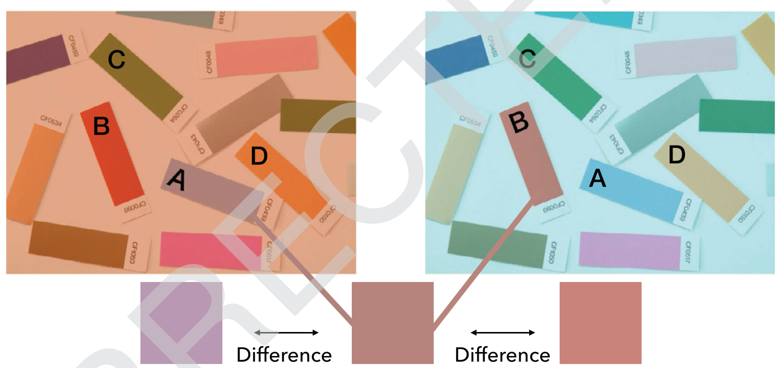

Fig. 2. Examples of color constancy. Although the colors of left A and right B appear to be different, the two colors are physically the same. Q2

To broaden this range, we focused on the property of human perception. The number of physically presentable colors is not always the same as the number of human perceivable colors. Humans perceive a color as a relative value affected by the surrounding elements. For example, as shown in Fig. 2, humans perceive colors A through D as relatively similar, regardless of whether the environmental light is orange or cyan. On the other hand, actual colors are altered from the environmental light. For example, the color of A in the left image and of B in the right image appear to be different colors. However, these two colors are physically the same. This is an effect of color constancy and is a type of visual illusion. The main purpose of numerous studies conducted on the use of projection is to present projected content to human viewers. In other words, even if the presented colors are physically incorrect, there will be no problem if the colors are perceptually correct. Our idea is to intentionally create differences between the physical and perceptual colors by inducing color constancy to perceptually broaden the presentable color range of a projector.

In this paper, we present an algorithm for determining a projected color for perceptually presenting a desired color that cannot be presented using a naïve light projection. To induce color constancy, the colors of both the target and surrounding areas must be modified. Our algorithm calculates suitable projection colors for both areas to present a desirable color. In addition, we conducted a user study to confirm that our algorithm can 1) induce color appearance shifts by color constancy, 2) broaden the presentable color range of a projector, and 3) shift a perceptual color toward the desired direction.

2. Related work

Our method controls the colors of real-world objects through light projection. This technique can be categorized as a type of spatial augmented reality (SAR). SAR is an augmented reality technique that visualizes virtual information in the real world, allowing viewers to observe information without a tablet PC or head-mounted display [6]. Raskar et al. [7] proposed the use of “Shader Lamps,” which can change the appearance of an object with a complex geometry by projecting images while avoiding geometric distortion. Based on their research, numerous studies have been conducted on solving geometrical problems when applying projection mapping onto various objects, such as rigid moving objects [8,9], deformable objects [10,11], and faces [12].

Numerous studies have also focused on reproducing a desired color appearance, which is also the aim of the present research. Nayar et al. [13] proposed a radiometric compensation technique using a color-mixing matrix between a camera and a projector. In addition, Grossberg et al. [14] proposed an off-line calibration method for achieving on-line compensation. Brown et al. [15] proposed a model-based method for controlling the brightness of a display produced by a multi-projector system. Although these approaches can only be applied under static situations, methods that

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can be applied under dynamic situations have also appeared. The method by Fujii et al. [16] can compensate the projected appearance in a dynamic environment using a feedback algorithm. Amano et al. [17,18] proposed an algorithm that estimates the reflectance of a real object and controls its appearance in real time by creating a feedback structure, and Akiyama et al. [19] extended it to robustly estimate reflectance in a dynamic light environment. These studies are physically based, and the appearance as perceived by a human reviewer is not considered.

Our study reproduces colors based on how they are perceived by humans. In the SAR field, color perception is considered based on several different color compensation techniques. Grundhöfer et al. [20] established a method for reproducing perceptually high-contrast images in a projected display. Ashdown et al. [21] proposed a method for producing a perceptually wider dynamic range for photometric compensation. Madi et al. [22] created a model of color constancy for reproducing the appearance of an object under different lighting conditions. Pjanic et al. [23] proposed a perception-based compensation technique for implementing a seamless multi-projection system by employing RLab, a type of color perception model. All previous techniques described above take human-perceived colors into consideration. However, most studies have focused on reproducing perceptually correct colors. This is different from our main goal: broadening the presentable color range of a projector.

Some studies have focused specifically on inducing a visual illusion. Kawabe et al. proposed a method for providing dynamic expression of static objects by projecting dynamic gray-scaled images [24], whereas Fukiage et al. [25] created a perceptual model to determine the suitable motion amount that humans can perceive as natural. Kawabe et al. also proposed a method for providing perceptual depth or transparency to letters or drawings on paper by visualizing virtual shadows [26]. The research described herein uses visual illusions that artificially create an expression that is difficult to create physically.

In this study, we induce a visual illusion of color using light projection to broaden the presentable color range of a projector. Some of the studies above have taken color perception into consideration, and some have induced a visual illusion. Unlike these studies, however, we induce a visual illusion of color to control the object colors perceptually. We extend our previous work that described the system [27,28] with a user study and evaluate the performance of our system. In this paper, we describe our new algorithm for calculating suitable projection colors and present desirable colors in a perceptual manner.

3. Projection technique for controlling perceived colors

In this section, we describe how to control the colors of objects perceptually by inducing color constancy. This section consists of two parts: one on inducing color constancy and the other on calculating a suitable projection color. We call our method projection-induced illusion (PII). We use the RGB color space for explanation.

3.1. Model for inducing the illusion

The perceived colors of objects remain relatively constant under varying but uniform illumination conditions owing to the effects of color constancy [29]. The human visual system estimates colors of illumination and negates their effects to allow the original colors of the objects to be perceived. In other words, if we can create a misperception regarding the color of the illumination for observers, we can induce an illusion and control the perceived colors of objects. Here, we describe how to create this misperception regarding color illumination for controlling object color through the use of a projector.

We introduce a photometric model which is shown in the research by Fujii et al. [16]. The irradiance measured by a camera is

$$C_i = \int (l(\lambda) + P_j\omega_j(\lambda))s(\lambda)q_i(\lambda)d\lambda \tag{1}$$

where $l(\lambda)$ is the irradiance on the scene by environmental light; P_j is the brightness of the projector for the j channel; $\omega_j(\lambda)$ is the spectral response for projector channel j, where λ is wavelength; and $s(\lambda)$ is the spectral reflectance of a surface and $q_i(\lambda)$ is the camera spectral response for color camera channel i. i, j are channels and $i, j = R, G, B$. Suppose that the camera and the projector each have three color channels (RGB). We assume that the reflectance of the surface is effectively constant within each of the camera bands. Thus, we can rewrite Eq. (1) as

$$C_i \approx K_i \int (l(\lambda) + P_j\omega_j(\lambda))q_i(\lambda)d\lambda \tag{2}$$

Using Eq. (2), we can denote the model at each pixel using vectors and matrices as

$$\mathbf{c} = \mathbf{K}(\boldsymbol{l} + \mathbf{V}\boldsymbol{p}) \tag{3}$$

where:

$$\mathbf{c} = \begin{pmatrix} c_R \\ c_G \\ c_B \end{pmatrix}, \mathbf{K} = \begin{pmatrix} k_R & 0 & 0 \\ 0 & k_G & 0 \\ 0 & 0 & k_B \end{pmatrix}, \boldsymbol{l} = \begin{pmatrix} l_R \\ l_G \\ l_B \end{pmatrix}$$

$$\mathbf{V} = \begin{pmatrix} v_{RR} & v_{RG} & v_{RB} \\ v_{GR} & v_{GG} & v_{GB} \\ v_{BR} & v_{BG} & v_{BB} \end{pmatrix}, \boldsymbol{p} = \begin{pmatrix} p_R \\ p_G \\ p_B \end{pmatrix}$$

$$\mathbf{V_{AB}} = \int \omega_B(\lambda)q_A d\lambda,$$

$$\boldsymbol{l}_A = \int l(\lambda)q_A(\lambda)d\lambda.$$

The interaction of spectral response of the projector and the camera are described by the color mixing matrix $\mathbf{V}$.

Fig. 3 shows the concept of our technique. We illustrate the case of changing the object color from red to sky blue through light projection. We regard the object's surface as Lambertian and focus only on diffuse reflection. We classify the object into two areas: the central and surrounding areas. The central area in the image on the left side of Fig. 3 is the red region, and the surrounding area is the gray region. The central area has reflectance $\mathbf{K_c} = \mathrm{diag}(k_{c,r}, k_{c,g}, k_{c,b})$, and the environmental light $\boldsymbol{l} = (l_r, l_g, l_b)^{\mathrm{T}}$ and projection are reflected onto the surface in the central area $\boldsymbol{p_c} = (p_{c,r}, p_{c,g}, p_{c,b})^{\mathrm{T}}$. Reflected light from the central area $\boldsymbol{r_c}$ is measured by the camera, and it is expressed as

$$\mathbf{c_c} = \mathbf{K_c}(\boldsymbol{p_c} + \boldsymbol{l}). \tag{4}$$

Our eyes capture this reflected light to sense the color of the central area. We refer to the physical color determined by the wavelength of light as the actual color. We regard the physically controllable range of projection $\boldsymbol{p_c}$ in each RGB channel as zero to p_{max}. The physically controllable range of the reflected light $\boldsymbol{r_c}$ is determined by this range of $\boldsymbol{p_c}$. When the target color is inside this range, the projector can present the target color by $\boldsymbol{r_c}$ physically as the actual color. When the target is outside this range, it is impossible to present it physically under this condition. In this case, we try to shift from the actual color to the target color perceptually by projecting $\boldsymbol{p_s}$ onto the surrounding area to introduce a misperception of an illumination color. We then introduce the target color with reflectance $\mathbf{K_t} = \mathrm{diag}(k_{t,r}, k_{t,g}, k_{t,b})$. As shown in Fig. 3, this target color is sky blue. When this sky blue object is under uniformly colored illumination, as indicated on the right side of Fig. 3, humans perceive the object color as sky blue in a relative manner owing to the color constancy effect. When the projection

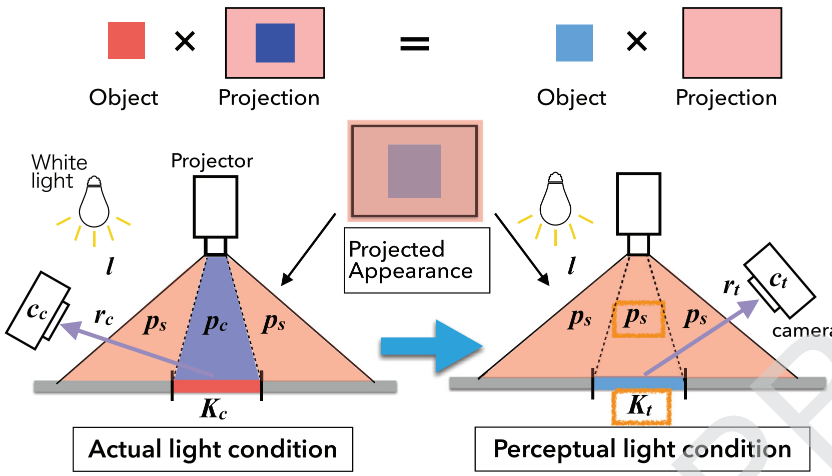

Fig. 3. Idea for inducing color constancy. When a projector actually projects illumination as shown on the left side, observers perceive that uniformed colored illumination is projected, as shown on the right side. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$\boldsymbol{p_s}$ and environmental light $\boldsymbol{l}$ are projected onto the area with reflectance $\mathbf{K_t}$, the reflected light $\boldsymbol{r_t}$ can be obtained by the camera as

$$\boldsymbol{c_t} = \mathbf{K_t}(\boldsymbol{p_s} + \boldsymbol{l}). \tag{5}$$

When the reflected lights $\boldsymbol{r_c}$ and $\boldsymbol{r_t}$ are the same, we can reproduce the light condition shown on the right side of Fig. 3 by projecting $\boldsymbol{p_c}$ and $\boldsymbol{p_s}$, similarly to the image on the left side of Fig. 3. By reproducing this perceptual light condition, observers perceive that the object with the target color $\mathbf{K_t}$ is under a uniform colored light $\boldsymbol{p_s}$. To obtain the projections $\boldsymbol{p_c}$ and $\boldsymbol{p_s}$ and present the target color, we must minimize the following cost function.

$$\boldsymbol{p_c}, \boldsymbol{p_s} \in \underset{\boldsymbol{p_c}, \boldsymbol{p_s}}{\arg\min} |\mathbf{K_c}(\boldsymbol{p_c} + \boldsymbol{l}) - \mathbf{K_t}(\boldsymbol{p_s} + \boldsymbol{l})| \tag{6}$$

When the result of Eq. (6) is zero, humans understand that a single colored uniform illumination $\boldsymbol{p_s}$ is projected, and the original color of the object is $\mathbf{K_t}$. However, using only this cost function, there are multiple answers to make the cost function zero. We cannot specify suitable projection colors $\boldsymbol{p_c}$ and $\boldsymbol{p_s}$ with Eq. 6 alone. We describe how to determine a suitable projection of colors in the next section.

3.2. Calculating suitable projection color

Our method projects colored illumination onto the surrounding areas even when we do not seek to change the colors of such areas. Thus, we define a suitable projection color of $\boldsymbol{p_s}$ as a color that is closest to achromatic.

With this algorithm, we focus on reproducing the target reflectance. In other words, we are not concerned with the brightness of the target color, and instead focus on the hue and color saturation in an HSV color space. When a projector can physically present the target color without applying our method, a $\boldsymbol{p_c}$ exists that satisfies the following:

$$\mathbf{K_c}(\boldsymbol{p_c} + \boldsymbol{l}) = g\mathbf{K_t}\boldsymbol{u} \tag{7}$$

where $\boldsymbol{u} = (1, 1, 1)^T$ and g is a scalar value. The left side of Eq. (7) indicates the RGB values of reflected light from a projected surface, and the right side shows the diagonal elements of the target reflectance. When there is no $\boldsymbol{p_c}$ satisfying Eq. (7), our algorithm finds $\boldsymbol{p_c}$ that can present a color which is close to the target color.

As the next step, we substitute the maximum power projection value $p_{\max}$ for $p_{c,r}$, $p_{c,g}$, or $p_{c,b}$, which have the minimum value in $\frac{k_{c,r}}{k_{t,r}}$, $\frac{k_{c,g}}{k_{t,g}}$, and $\frac{k_{c,b}}{k_{t,b}}$. By applying this step, we can set one of the three values, $p_{c,r}$, $p_{c,g}$, or $p_{c,b}$. The following equation is a deformation of Eq. (7) accomplished by division into each RGB element.

$$\frac{k_{c,r}}{k_{t,r}}(p_{c,r} + l_r) = \frac{k_{c,g}}{k_{t,g}}(p_{c,g} + l_g) = \frac{k_{c,b}}{k_{t,b}}(p_{c,b} + l_b) \tag{8}$$

Using the determined value, we can calculate the other two values with Eq. (8). When all values are inside the presentable range of the projector $0 \le p_{c,i} \le p_{\max}$ $(i \in \{r, g, b\})$, the target color can be presented physically by projecting the obtained projection color $\boldsymbol{p_c}$. However, these values are occasionally negative, indicating that they are impossible to project using a projector. In these cases, we calculate the projection color for the surrounding area $\boldsymbol{p_s}$ to present the target color perceptually.

As we described before, when the residual of the cost function in Eq. (6) is zero, color constancy will be induced. We then calculate $\boldsymbol{p_s}$, which makes the residual zero based on the calculated $\boldsymbol{p_c}$. First, we substitute zero for $p_{c,r}$, $p_{c,g}$, and $p_{c,b}$, which have negative values. Through this process, we can obtain all values of $\boldsymbol{p_c}$. By substituting a zero value, a physical difference occurs between the target color and the reflected light. However, this will be compensated perceptually by the color projected onto the surrounding areas $\boldsymbol{p_s}$. Here, $\boldsymbol{p_s}$ can be calculated through the following equation.

$$\boldsymbol{p_s} = \mathbf{K_c}./\mathbf{K_t}(\boldsymbol{p_c} + \boldsymbol{l}) - \boldsymbol{l} \tag{9}$$

where ./ indicates element-wise division. Here, $\boldsymbol{p_s}$, calculated using Eq. (9), and $\boldsymbol{p_c}$ make the residual of the cost function in Eq. (3) zero. Thus, we can induce color constancy and present the target color by projecting $\boldsymbol{p_c}$ onto the center area and $\boldsymbol{p_s}$ onto the surrounding area. When all values of $\boldsymbol{p_c}$ are positive, the calculated values become $p_{s,r} = p_{s,g} = p_{s,b}$, which means that $\boldsymbol{p_s}$ is an achromatic color. In addition, when the original and target colors are too far from each other, $\boldsymbol{p_s}$ may have a negative value. This means that the target color cannot be presented, even perceptually, with such a setup. We show the calculation explained in this section to calculate projection colors $\boldsymbol{p_c}$ and $\boldsymbol{p_s}$ as follows in the form of an algorithm.

4. Experiment

We conducted a user study to confirm the following three hypotheses, namely, that our method can 1) create a misperception regarding the color of illumination, 2) broaden the presentable

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Algorithm 1 Algorithm for calculating projection color to the central and surrounding areas.

Input: Target reflectance $K_t = diag(k_{t,r}, k_{t,g}, k_{t,b})$,
original reflectance $K_c = diag(k_{c,r}, k_{c,g}, k_{c,b})$,
environmental light $\boldsymbol{l} = (l_r, l_g, l_b)^T$
Output: Projection color $\boldsymbol{p_c}$ and $\boldsymbol{p_s}$

calculate $x \leftarrow \frac{k_{c,r}}{k_{t,r}}, y \leftarrow \frac{k_{c,g}}{k_{t,g}}, z \leftarrow \frac{k_{c,b}}{k_{t,b}}$

if $(x = min(x, y, z))$ **then**

$p_{c,r} \leftarrow p_{\max}$

$$p_{c,g} = \frac{k_{c,r}k_{t,g}}{k_{t,r}k_{c,g}}(p_{c,r} + l_r) - l_g$$

if $p_{c,g} < 0$ **then** $p_{c,g} \leftarrow 0$ **endif**

$$p_{c,b} = \frac{k_{c,r}k_{t,b}}{k_{t,r}k_{c,b}}(p_{c,r} + l_r) - l_b$$

if $p_{c,b} < 0$ **then** $p_{c,b} \leftarrow 0$ **endif**

else if $(y = min(x, y, z))$ **then**

$$p_{c,g} = p_{\max} p_{c,r} = \frac{k_{c,g}k_{t,r}}{k_{t,g}k_{c,r}}(p_{c,g} + l_g) - l_r$$

if $p_{c,r} < 0$ **then** $p_{c,r} \leftarrow 0$ **endif**

$$p_{c,b} = \frac{k_{c,g}k_{t,b}}{k_{t,g}k_{c,b}}(p_{c,g} + l_g) - l_b$$

if $p_{c,b} < 0$ **then** $p_{c,b} \leftarrow 0$ **endif**

else if $(z = min(x, y, z))$ **then**

$$p_{c,b} = p_{\max} p_{c,r} = \frac{k_{c,b}k_{t,r}}{k_{t,b}k_{c,r}}(p_{c,b} + l_g) - l_r$$

if $p_{c,r} < 0$ **then** $p_{c,r} \leftarrow 0$ **endif**

$$p_{c,g} = \frac{k_{c,b}k_{t,g}}{k_{t,b}k_{c,g}}(p_{c,b} + l_b) - l_g$$

if $p_{c,g} < 0$ **then** $p_{c,g} \leftarrow 0$ **endif**

end if

$$p_{s,r} = \frac{k_{c,r}}{k_{t,r}}(p_{c,r} + l_r) - l_r$$

$$p_{s,g} = \frac{k_{c,g}}{k_{t,g}}(p_{c,g} + l_g) - l_g$$

$$p_{s,b} = \frac{k_{c,b}}{k_{t,b}}(p_{c,b} + l_b) - l_b$$

return $\boldsymbol{p_c} = (p_{c,r}, p_{c,g}, p_{c,b})^T, \boldsymbol{p_s} = (p_{s,r}, p_{s,g}, p_{s,b})^T$

color range of a projector, and 3) shift the perceptual colors toward the desired directions. In this section, we describe the details of the user study and the results.

4.1. Procedure

We used six colors in the third row of X-rite Color Checker, which is shown in Fig. 4 (a). We controlled the reflected light from the color checker through a projection and compared the perceived colors using two methods: our method and naïve overlaying projection. Naïve overlaying projection retains the projection to the surrounding area $\boldsymbol{p_s}$ as a constant achromatic color to avoid inducing an illusion like our method. However, naïve projection method also calculates projection color to the target area $\boldsymbol{p_c}$ by estimated reflectance and measured environmental light using the method proposed by Amano et al. [17]. We changed the six original colors in the Color Checker to six other colors that are the farthest from them, namely, red, green, blue, yellow, magenta, and cyan, respectively. For example, when we change from red, we change to red, green, blue, yellow, magenta, and cyan as much as possible. The six directions under this situation are shown in Fig. 4 (b). Our method presents the perceptually farthest colors with an illusion, and the naïve overlaying projection presents the physically farthest colors without an illusion. There were 6 original colors applied × 6 directions × 2 methods, for a total of 72 conditions applied. We used an EPSON EH-TW5650 projector to control the colors and a XIMEA MQ013CG-E2 camera for monitoring the controlled colors.

Ten naïve participants took part in this experiment, and all participants had normal or corrected-to-normal visual acuity and normal color vision. Each participant was asked to perform a matching task. We changed one color into another using a projection, and the participants viewed the projected color and found the closest matching color from a color sample (PANTONE Formula Guide Solid Uncoated). We set a color of illumination of the experimental room as white and made luminance to the projection targets and the color sample the same. In this study, we focus on human perceived color, not physical value. Because of these reasons, we did not measure chromaticity of projection targets and the color samples. A number (1 6) was assigned near each target color to tell participants which target color to make a match. A color sample, which the participant could see freely, was then placed near the participant. Although the participants could see the projected target and the color sample any number of times, we requested them to report as quickly as possible. The amount of time required for the entire experiment was approximately 30 min, and no breaks were taken.

Each participant completed a matching task for all conditions in a randomized order. A total of 74 conditions were applied. In our experimental environment, the projection was identical between our method and the naïve approach under four of the conditions as a result of the above calculations. We therefore removed four of the 72 conditions. However, the participants also conducted a matching task for each of the six colors under white illumination, thus returning the number of conditions to 74.

An overview of the experimental setup is shown in Fig. 5 (a), and the configuration of the equipment is shown in Fig. 5 (b). The participants sat near the camera to make certain that lights reflected to the camera and the participant's eyes were mostly the same. The color sensitivities of a camera and of human eyes are different, and thus the colors captured by a camera and the perceived colors may differ as well. However, to use a camera to measure the intensity of the reflected light in each pixel, we set the gamma of the camera to 1. Thus, we do not assume that the captured images and the perceived appearance are the same. In addition, we set the distance between the color checker and the participant to approximately 1.5 m, and the luminance of the environment is set as approximately 1000 lx.

4.2. Results

We examined the following two aspects of applying our PII from the available data: whether the presentable color range can be broadened, and whether the perceptual color can be shifted toward the desired direction. To answer the first question, we computed the average values of each condition from the results of all participants. We plotted these average values and filled in the surrounding regions on a u'v' color chromaticity diagram in an attempt to evaluate in a color space that reflect perceptual uniformity. The results of our method are represented by the blue region and the red region in the results without our method. The results are shown in Fig. 6. Under all conditions applied, the blue colored regions are larger than the red colored regions. We also calculated the amplification ratio between the regions of the naïve projection and our method. The presentable color ranges on the u'v' diagrams are at least 1.3- and at most 6-times larger. The values for each color are shown in Fig. 6.

Second, we examined whether our method can shift the perceptual color in the desired direction. We computed pairs of vec-

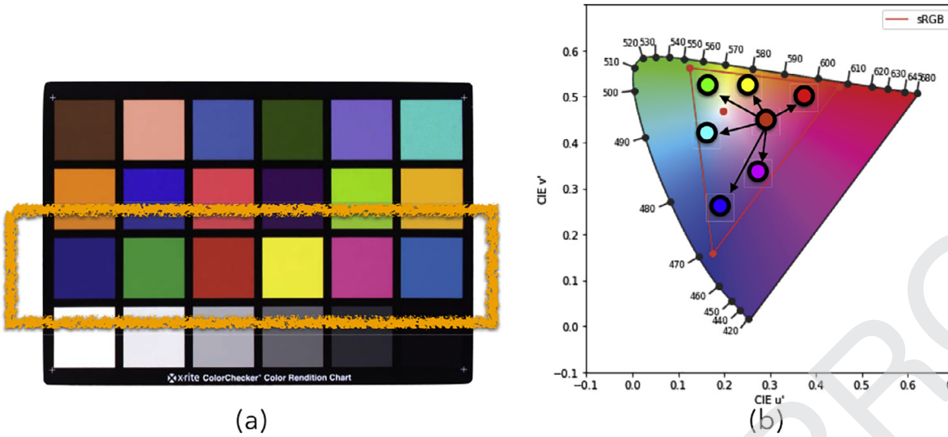

Fig. 4. (a) The six colors within the orange frame are used as the projection target in the user study. (b) Examples of six directions when we control the color from red during the user study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

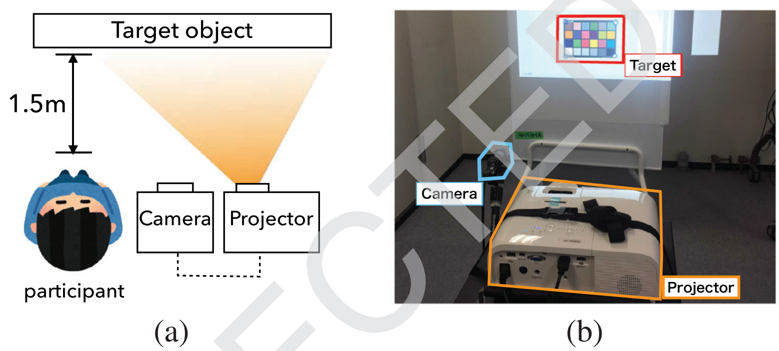

Fig. 5. Overview of experiment setup. (a) Layout of participants and our system. (b) Actual experimental environment.

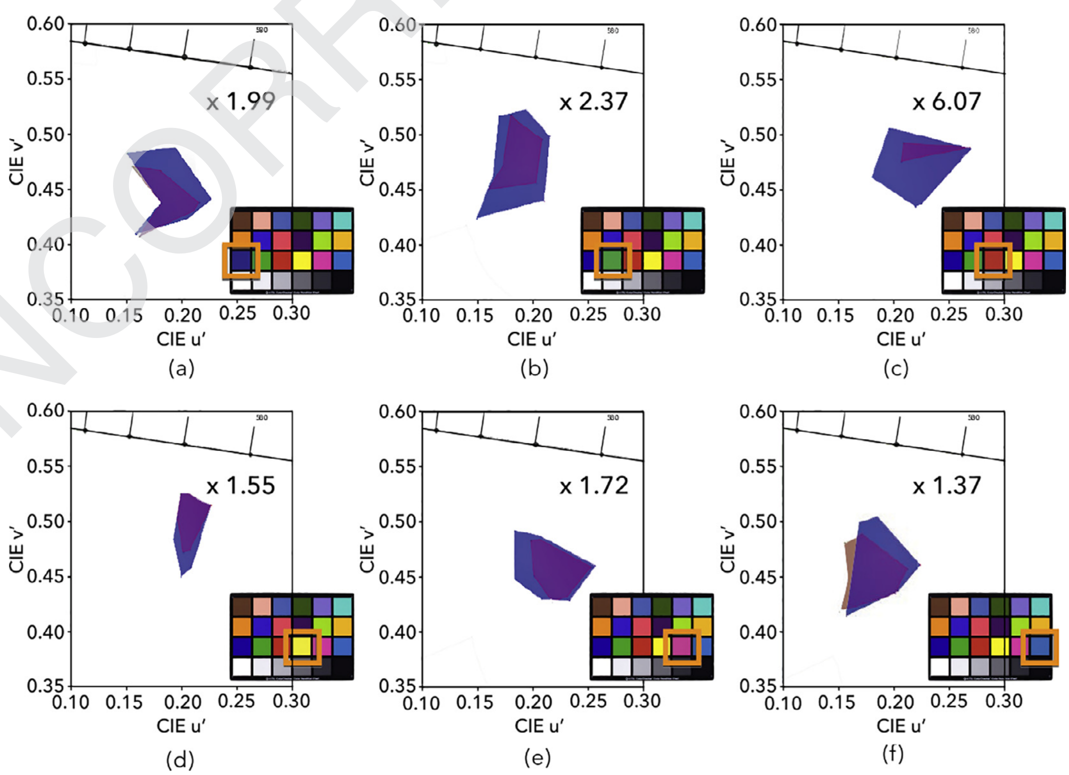

Fig. 6. The presentable color ranges of each original color using naïve projection and our PII method. The results of the naïve projection are shown in translucent red, and those of our PII method are shown in blue. The numbers shown in the upper-right of each figure represent the ratio of each pair of regions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tors, namely, vectors from the original colors to the resulting colors through naïve projection, and vectors from the original colors to the resulting colors by our method. We then calculated the offset angles for each pair. When the calculated angles are near zero, it indicates that our method can shift the perceptual colors in the desired directions, which are the same as the directions used by the naïve projection. The box plots are shown in Fig. 7. We examined the directions by checking whether the angles were concentrated at low values. We drew dotted lines at 30 degrees as a reference for visual clarity. Using our current technology, it is difficult to present the perceptual colors in a precise manner, and there are individual differences in color perception. Thus, we examined the directions roughly using this method. As a result, when the target colors and the original colors were the same or similar, the angles increased. By contrast, when the target colors and the original colors were far from each other, the angles decreased. This tendency can also be found from the results of length shown in Fig. 8.

We compared the lengths of the same pairs of vectors using a one-sided *t*-test to determine whether our method can represent more distant colors as compared to those of the naïve projection. The results are shown in Fig. 8. We found that there are significant differences between the two when the original color and the target color have a completely or nearly completely complementary color relationship. For example, when the original color is blue, there are significant differences in the cases of red, green, or yellow, which are far away from blue. In contrast, the other colors, blue, magenta, and cyan, mainly contain a blue element and are close to blue. From these results, we conclude that our method can broaden the presentable color range of a projector toward the complementary directions. Judging from the results presented here, our PII method can broaden the presentable color range of a projector toward the complementary color direction from the original color of the object and accurately control the perceptual color. By contrast, our PII method is not as effective when the chromaticity levels of the original and target colors are similar.

We also calculated the length from the resulting colors by our method and by naïve projection to the each target color and compared the length using a one-sided t-Test. The results are shown in Fig. 9. We found there are significant differences between the two when the original color and the target color have a completely or nearly completely complementary color relationship, which is same result of previous test shown in Figs. 8 and 9.

5. Discussion

From the user study, we found that our method is effective when the original color of an object and the target color have a nearly complementary color relationship. We believe that there are two main reasons for this, which are caused by the characteristics of color constancy.

First, the human visual system estimates the color of the illumination and weakens the color sensed by the eyes to perceive the original colors of the actual object in a relative manner [29]. When the resulting colors are already saturated in chromaticity, it becomes difficult to weaken any elements of RGB to make the color more saturated. We believe that we can explain the results of the user study based on this characteristic. In Figs. 7 and 8, when the original colors and the target colors are similar, the angles become larger with no significant difference in length. We believe that this occurs because the colors resulting from the naïve projection are sufficiently deep, and the color constancy effect weakens. In addition, when the target colors mainly contain elements of the original color, the results are similar. For example, in Fig. 7, when the original color is green, the results of green, yellow, and cyan are greater than 30°. In these cases, yellow primarily contains green and red, and cyan contains green and blue. Thus, the color constancy effect is also not excessive in these cases, and the errors increase.

Second, the color constancy effect is powerful when the actual colors are near a non-color [30]. The human visual system easily distinguishes gray from non-gray. However, it is not as easy to distinguish two nearly non-gray colors when they are deep, even if the difference between the two colors is the same as that between the gray and non-gray cases [31]. When changing to complementary colors, the actual resulting colors become near gray, and the perceptual colors shift from this color when using our PII method. In this case, the perceptual colors can be shifted dynamically.

The case of the original color, i.e., red, and the target color, i.e., blue in Fig. 7, cannot be explained with the color constancy effect described above because the resulting angle is not a small and concentrated angle, despite red and blue being distant colors. We suppose that this is due to the brightness of the surface. People perceive blue as darker than green even if the intensities of the two colors are identical [32]. In addition, people perceive blue as darker under well-lit environments as compared to dark environments through the Purkinje effect [33]. For these reasons, the resulting colors were perceived as dark, and the answers from the participants are unstable.

Our experimental results and the present discussion reveal an effective aspect regarding our proposed method. Our method is helpful in presenting a color which is distant from the original color, such as a complementary color. Although our method is not very effective when the original and target color are similar, the target color can be presented through a simple naïve projection under this situation. The purpose of this study is to create a method that can perceptually represent colors that cannot be presented physically. From this viewpoint, the limitation is not a significant problem and our method is effective regarding its intended purpose.

In this research, we focus on changing only one color to another color. As an application, we hypothesize that this research can be used when we would like to display digital images on a colored wall. Usually, walls do not contain many colors. Thus, each wall has each color, which is difficult to be presented by projection. For example, when we seek to visualize something on a red wall, it is difficult to present a cyan color. In this case, our system can shift a presentable color range to the cyan direction by projecting red light to the surroundings.

6. Limitations and future work

There are several issues remaining to be addressed. First, our method does not consider the necessary size of the projection onto the surrounding areas. Currently, when our system induces color constancy, the system projects the surrounding projection as broadly as possible. We do not require much of the broad chromatic colored projection to induce color constancy. However, there have been no studies regarding the necessary area for inducing color constancy. To employ an effect of color constancy, observers need to misperceive the projection onto the surrounding areas as having uniform illumination in all areas. Thus, if the projection to the surrounding areas is too narrow, similar to projecting only onto the edges of the target area, color constancy will not be induced. As a future study, we will seek to determine the minimum area of projection onto the surrounding area for inducing color constancy by conducting a user study to minimize the discomfort occurring by colored illumination onto the surrounding areas. When colored illumination cannot be projected onto a surrounding area, it is difficult to induce color constancy. Under this situation, it may be possible to employ other illusions, such as a watercolor illusion [34]. Such an illusion is induced by the colors of the edges, and the perceived colors shift perceptually [34,35].

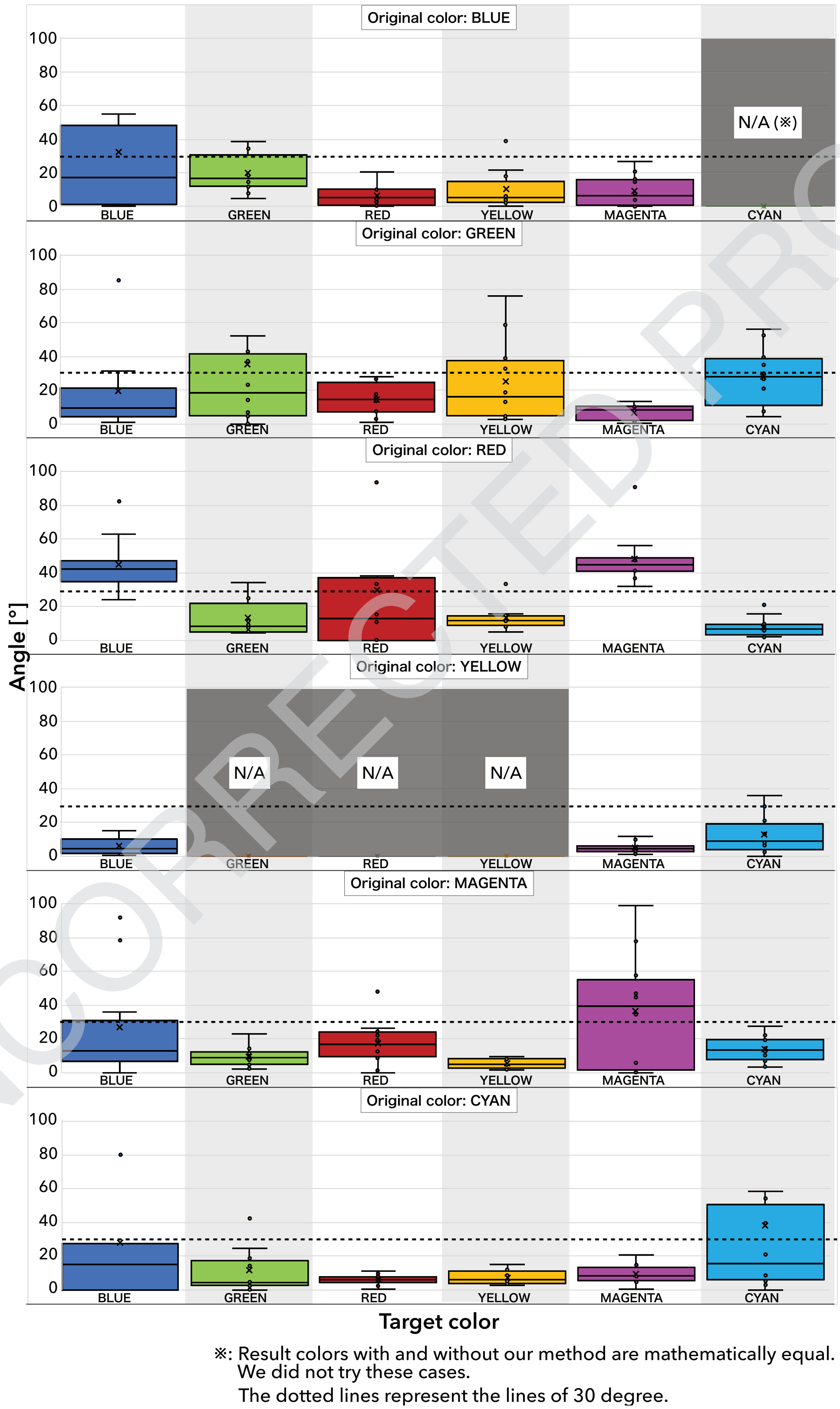

Fig. 7. The results of angles between pairs of vectors: (1) from the original colors into the resulting colors through a naïve projection, and (2) from the original colors to the resulting colors using our PII method. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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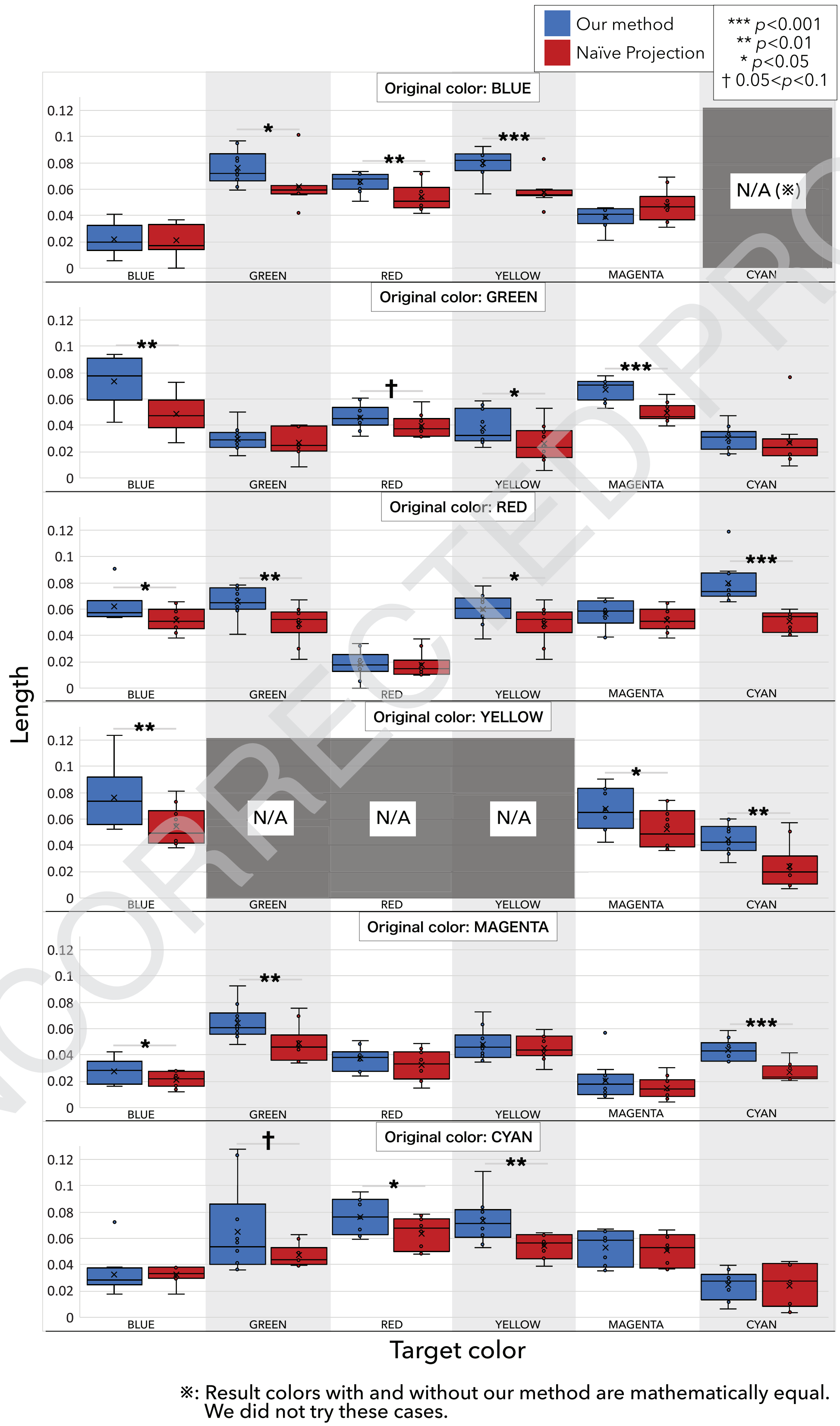

Fig. 8. Results of the comparison between vector lengths: from the original colors to the resulting colors using (1) naïve projection and (2) our PII method. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

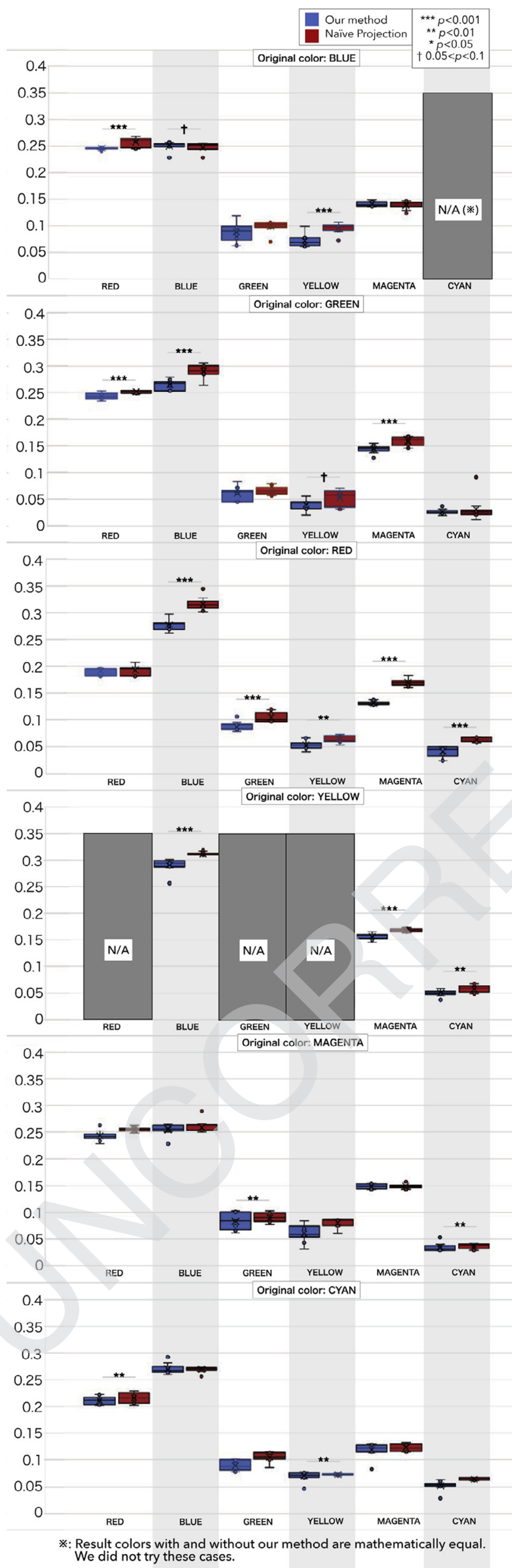

Fig. 9. Results of the comparison between lengths on the u'v' chromaticity diagram: from the target colors to the resulting colors using (1) naïve projection and (2) our PII method. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Second, we assume that humans have perfect color constancy in their vision system. This means that humans can perfectly eliminate the effects of colored illumination and completely perceive the original colors of real objects. In fact, however, humans do not possess such a perfect color constancy. When the color of illumination is deep, the perceived color is shifted. For example, when humans see blue objects under red illumination, we can perceive the object color as a reddish-blue color, not the true blue. For this reason, our system cannot estimate the accuracy of the perceived colors. For an accurate perceptual color reproduction, we require the use of a color appearance model of the imperfect color constancy of humans. RLAB, proposed by Fairchild [36], or a color appearance model, proposed by Kuriki [37], take the appearance under colored illumination into consideration. By employing these color appearance models, our method may represent perceptual colors more accurately.

For the experiments in this paper, we did not measure the illuminant condition. We used the fluorescent light in the room as environmental light, therefore keeping the lighting of the target objects and color samples the same. Thus, we examined the amount of change of the colors under fluorescent light to the colors with projection. However, environmental light may affect to the resulting colors of the system. In this paper, we did not investigate the effects of environmental light on the perceived colors that the system can control. We will investigate how well the system can control colors under various environmental light conditions in the future.

The current algorithm focuses on changing one color to another. In other words, our system currently cannot change multiple colors. There are two solutions to applying multiple colors. One is simply creating a large perceptually uniform colored illuminated area that includes multiple target areas inside it. However, this solution can be used when all directions from each original color to each target color are similar. For example, changing both red and green regions toward the blue direction is possible. In contrast, when we would like to change a red region into green and a green region into blue, it is not possible to present both colors while using a single uniform illumination. In this case, when multiple regions are geometrically separated, we can create multiple perceptually uniform color illuminated areas. However, this means that several separate areas that are illuminated with different illumination exist in a single scene. This is an unusual situation, and may result in discomfort. These two solutions are already possible with current technology. In addition, we hypothesize that the possibility to expand our method by employing other visual illusions exists. There are several illusions which alter perceptual colors of an area due to colors of the edges of the area. For example, humans perceive colorfulness of achromatic areas with colorful edges [34], and humans perceive the brightness of surfaces differently when the edge brightness is different, even if the actual brightness is identical [38]. By employing these kinds of illusions, we hypothesize that there is a possibility to change surface colors perceptually without changing the broad areas of the surroundings.

7. Application

Based on our method, we developed an application that can automatically control perceptual colors by inducing an illusion. The system consists of a projector, a camera, and a computer. Currently, we are focusing on changing one color to another. We must select one color from a captured image as an original color and select another color as the desired color. After selection, the system automatically creates a projection image to present the desired color. If the desired color can be presented without our method, a projection of the color onto the surrounding areas will be achromatic. In contrast, if the desired color cannot be presented using a

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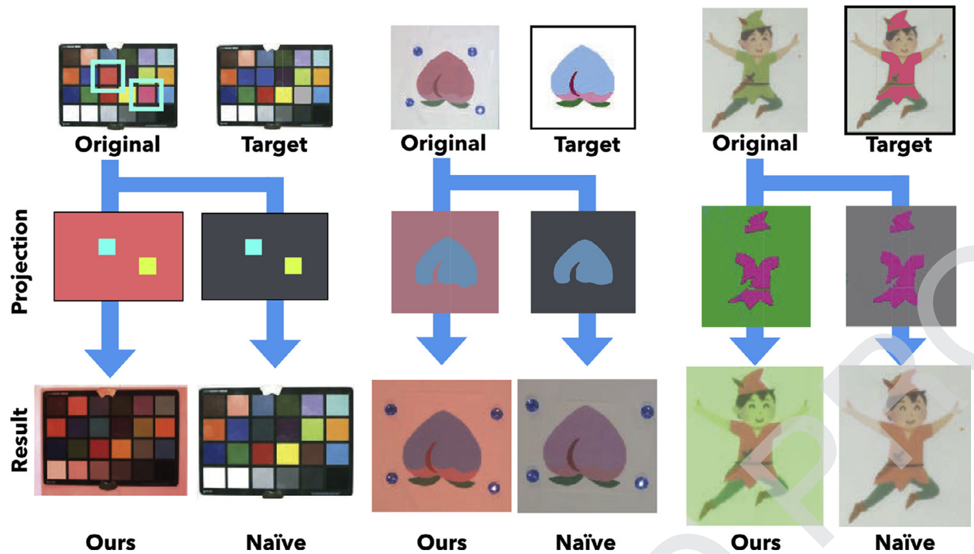

Fig. 10. Projection results. This figure shows the controlled appearance using our method and a naïve projection.

naïve projection, a color projected onto the surrounding areas will be chromatic and induce color constancy. Three projected results are shown in Fig. 10. In the third row, the resulting images using our method and naïve projection are shown. Although the physical colors of each of the pairs are completely the same, the perceptual colors differ. Colors of the results obtained by the proposed method are more similar than each target color.

As a real-world application of this study, we believe that we can classify applications of this study into 2 groups.

1. presenting colors which cannot be presented in that condition physically.
2. presenting colors which cannot be perceived normally for someone.

In first group, we think we can use our technique for advertisements or entertainments. By dynamically changing the colors of printed posters or real objects, they can more effectively catch the attention of viewers. In an actual scene, environments are too bright to use a projector. However, various colors can be represented through our method: compared to naïve overlaying projection, colors of static objects can be controlled dramatically. In addition, we believe that projection mapping events can occur under well-lit indoors when applying our approach. Most projection mapping events are held outside at night or in a dark room to obtain a sufficiently presentable color range of the projector. When environmental light is too bright like in the daytime outside, it is very difficult for our eyes to perceive projected colors. In that case, our method also cannot be used. However, using our method, the presentable color range can be broadened, and we may obtain a sufficient color range for the projection mapping. Moreover, we believe our method to be helpful in visualizing annotations in the real world using projection. In the context of augmented reality, substantial research is conducted for visualizing annotation on HMDs or on physical surfaces using projection. When users desire to show specific colored annotations on colored surfaces with projection, it may sometimes be very difficult because of the color of the surface. In this case, our method represents annotations with difficult colors on the surface.

In addition, as a example in 2nd group of applications, we believe that our system offers the possibility to support the vision of color-deficient individuals, who have difficulty perceiving specified colors owing to an anomaly or lack of cones. In other words, their brains are the same as those of individuals with normal vision, and they also possess a color constancy system. Our system can shift their perceptual colors without changing the actual colors. Thus, even if such individuals cannot perceive a specified color, our system may show colors that they normally cannot see. Studies supporting color-deficient individuals using devices such as mobile phones [39], OST-HMDs [40], or projectors [18] have been conducted. There are also lenses that block the confusing wavelengths of light for use in glasses [41] or contact lenses [42]. There are recoloring research for color-deficient individuals as well [43]. While these studies are helpful to distinguish confusing colors, they do not indicate that users can see colors which they usually cannot see. We believe that our method has the potential to show colors which color-deficient individuals cannot see, which would be a powerful application.

8. Conclusion

We designed a projection technique that can broaden the presentable color range of a projector perceptually by inducing color constancy. Through a user study, we examined our method to determine whether it can 1) induce color constancy, 2) broaden the presentable color range of a projector, and 3) shift the perceptual colors toward the desired directions. As the results indicate, the first two aspects were confirmed. For the third, our method can shift perceptual colors toward the desired direction when the original color and the target color are dissimilar. Despite the limitations of the original and target colors, our method is effective for perceptually presenting colors that are difficult to present physically.

In the research field of augmented reality, perceptual-based approaches have been recently proposed [25,44–46]. These approaches employ the effects of the human visual system to achieve research goals that are physically difficult or otherwise impossible. Perceptual-based approaches offer the possibility to overcome the limitations of physical-based methods. We believe that we must take perception into consideration when applying augmented reality.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Ryo Akiyama: Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing, Validation, Funding acquisition. **Goshiro Yamamoto:** Methodology, Writing - review & editing, Funding acquisition. **Toshiyuki Amano:** Methodology, Writing - review & editing, Resources. **Takafumi Taketomi:** Writing - review & editing. **Alexander Plopski:** Writing - review & editing. **Yuichiro Fujimoto:** Writing - review & editing. **Masayuki Kanbara:** Writing - review & editing. **Christian Sandor:** Writing - review & editing. **Hirokazu Kato:** Supervision, Resources.

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