Proposal of Minimization Problem Based Lightness Modification Method Considering Visual Characteristics of Protanopia and Deuteranopia

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***Abstract*—Color is important for humans to receive visual information such as from traffic lights and maps. However sometimes important color-based information cannot be correctly received by some visually impaired people such as protanopes and deuteranopes. It is necessary to understand their difficulties in perceiving color and provide solutions to improve their quality of life. In our paper, a lightness modification method that can convey the color-based information to protanopes and deuteranopes is proposed. By considering color differences in an input image, the proposed method modifies the output lightness of an image for protanopes and deuteranopes to preserve its visual detail. The proposed method only changes the lightness without changing the hue, resulting in the output image having natural colors. In experiments, we use six color blindness test images with different color distributions and compare the proposed method with three existing methods. The experiment results and their quantitative evaluation show that our proposed method is reliable and effective.**

I. Introduction

Color is very important for receiving visual information. However, color information cannot always be correctly received by all people. Color vision deficiencies exist almost one in twelve men worldwide, which is a very high ratio. Some people with color vision deficiencies can see as clearly as normal people but cannot discriminate certain colors. There are several types of color vision deficiency. The most common type is red/green color vision deficiency. People with this deficiency cannot distinguish some shades of red and green as shown in Fig. 1. Figs.1(b) and 1(c) are simulated images observed by people with protanopia and deuteranopia, respectively, which were obtained using the color vision model proposed by Viénot et al. [1].

(a) (b) (c)

Fig. 1. Color images observed by people with: (a) normal trichromacy, (b) protanopia, (c) deuteranopia.

The human visual system has three types of cones: red, green, and blue cones. Their photoreceptors are sensitive to light with different wavelengths, and colors are perceived on the basis of the ratio of their responses. Visual impairments can be classified as monochromacy, dichromacy, and anomalous trichromacy according to the conditions of the cones. Because people with monochromacy are very rare and anomalous trichromacy cause few problems in everyday life, we focus on the frequent types of dichromacy (protanopia and deuteranopia). People with protanopia do not have red cones, which are sensitive to long wavelengths, making it difficult for them to distinguish colors in the green-yellow-red region of the spectrum. Meanwhile, people with deuteranopia do not have green cones, which are sensitive to medium wavelengths. The appearance of colors for deuteranopes is very similar to that for protanopes.

Providing the detailed information from color images for visually impaired people is a very significant problem. To address this issue, several methods [2]–[18] have been proposed. These usually involve changing the hue in an input image to shows details. For example, Huang's method [5] change involves the hue in the $L^*a^*b^*$ color space and Milić's method [13] clustering the colors and changing them in the $Lu'v'$ color space. These methods change the color in an input image into considerably different colors so that the information in the original image can be observed by people with color vision deficiency. However, such color modification changes the impression of the original image and is not suitable for natural images. Another approach is to change the lightness, as employed in Tanaka's method [7], Takimoto's method [11] and Tennenholtz's method [15]. Their methods only change the lightness of the input image so that the color of the output image is not significantly different from that of the original image. We have also proposed such a method [18].

In this paper, a lightness modification method that yields barrier-free color images for protanopes and deuteranopes is proposed. Our proposed method is based on our previous work [18] because we do not want to change the hue of the original image. In the proposed method, we use the a^* component in an input color image in the lightness modification. The modification coefficient is determined by solving a minimization problem that considers the information of colors in an input image.

The remainder of this paper is organized as follows: Our proposed method is described in §II. In §III, the validity of the proposed method is confirmed through experiments. Finally, conclusions are given in §IV.

II. Proposed Method

In this section, we will introduce our new lightness modification method which is based on our previous method [18]. A schematic diagram of the proposed lightness modification method is shown in Fig. 2. As shown in the figure, the novel points of the proposed method are the lightness modification using the a^* component and the definition of weight in a minimization problem. These are explained in §II-A and §II-C, respectively.

A. Lightness Modification and Modification Coefficient

We use the a^* component in an input image in the lightness modification. The tentative modified lightness $\tilde{L}_i^*$ of the ith pixel is obtained as follows:

$$\tilde{L}_i^* = L_i^* + ca_i^*. \tag{1}$$

The modification coefficient c is obtained for each input image by solving the following minimization problem:

$$\tilde{c} = \arg\min_{c \in \mathbb{R}} E(c), \tag{2}$$

where E is an objective function and its definition is given in the next section. $\mathbb{R}$ in (2) means the real number. By substituting $\tilde{c}$ into c in (1), the tentative modified lightness $\tilde{L}^*$ is obtained.

B. Objective Function

The objective function E in the proposed method is defined as follows:

$$E(c) = \sum_{(i,j)\in\sigma_\rho} w_{ij}((\tilde{L}_i^* - \tilde{L}_j^*) - \delta_{ij})^2. \tag{3}$$

Form of the objective function, the definition of δ_{ij}, and σ_ρ in the proposed method are same to those in the our previous method [18]. δ_{ij} and σ_ρ are explained in this section. On the other hand, the definition of w_{ij} is different from our previous method and it will be explained in the next section.

δ_{ij} in (3) is the signed color distance between the ith and jth pixels and it is defined as

$$\delta_{ij} = \begin{cases} \Delta L_{ij}^*, & \sqrt{(\Delta L_{ij}^*)^2 + (\Delta b_{ij}^*)^2} > |\Phi_\alpha(\Delta a_{ij}^*)|, \\ \Phi_\alpha(\Delta a_{ij}^*), & \text{otherwise} \end{cases} \tag{4}$$

with

$$\Phi_\alpha(x) = \alpha \tanh(x/\alpha). \tag{5}$$

ΔL_{ij}^*, Δa_{ij}^*, and Δb_{ij}^* are $L_i^* - L_j^*$, $a_i^* - a_j^*$, and $b_i^* - b_j^*$, respectively. $|\cdot|$ in (4) stands for the absolute value. α in (5) is a parameter that determines the consideration of Δa_{ij}^*. Protanopes and deuteranopes find it difficult to distinguish Δa_{ij}^* while they can basically distinguish ΔL_{ij}^* and Δb_{ij}^*.

σ_ρ in (3) is the set of pixel pairs (i, j) which satisfy $d(i, j) \leq \rho$. Here, $d(i, j)$ means the chessboard distance [19] between the ith and jth pixels. That is, ρ is the size of neighborhood range.

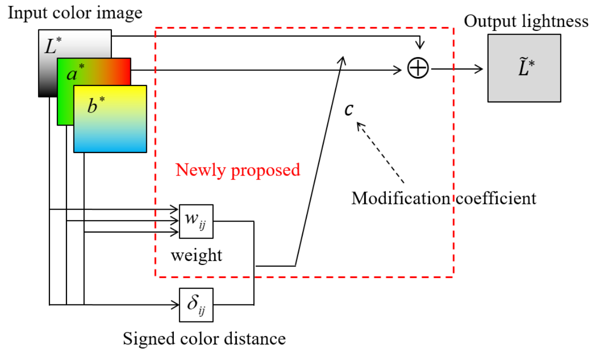
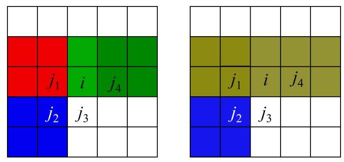


Fig. 2. Schematic diagram of the proposed lightness modification.



(a) (b)

Fig. 3. Example of color distribution: (a) normal color vision, (b) protanopia (or deuteranopia).

C. Weighting Considering with $L^*a^*b^*$ Components

The new weight w_{ij} is defined using ΔL_{ij}^*, Δa_{ij}^*, and Δb_{ij}^* as follows:

$$w_{ij} = w_{ij}^{L^*} w_{ij}^{b^*} w_{ij}^{a^*} \tag{6}$$

with

$$w_{ij}^{L^*} = \exp\left(-\frac{(\Delta L_{ij}^*)^2}{2\lambda_{L^*}^2}\right), \tag{7}$$

$$w_{ij}^{b^*} = \exp\left(-\frac{(\Delta b_{ij}^*)^2}{2\lambda_{b^*}^2}\right), \tag{8}$$

and

$$w_{ij}^{a^*} = 1 - \exp\left(-\frac{(\Delta a_{ij}^*)^2}{2\lambda_{a^*}^2}\right). \tag{9}$$

As defined in (4), when ΔL^* and/or Δb^* is efficiently larger than Δa^*, ΔL^* is directly used. However, this sometimes cause bad effect. For example, in Fig. 3(a), the ith and j_1th pixels have similar lightness and surround by white background. The lightness differences between the background and the two colors are large that they will be retained after solving the minimization problem. This prevents the lightness of the two colors from being modified. It is unnecessary to consider the relation between the ith pixel and background pixels such as the j_3th pixel. To solve this problem, we have defined $w_{ij}^{L^*}$ to consider the lightness difference so that we can ignore the pixel pairs which ΔL^* is large.

As shown in Fig. 3(b), people with protanopia and deuteranopia can distinguish Δb^* for the ith and j_2th pixels. Then we have defined $w_{ij}^{b^*}$ to disregard pixel pairs for which Δb^* is large.

There is another situation like the ith pixel and j_4th pixel, even the normal vision people hard to know the difference between those two colors. So we introduce $w_{ij}^{a^*}$ to ignore the similar color which is hard to distinguish by normal people. This introduction of $w_{ij}^{a^*}$ is a new point of the proposed method. In our previous method, w_{ij} is defined as $w_{ij}^{L^*} w_{ij}^{b^*}$.

λ_{L^*} is the parameter which is used to control the contribution of ΔL^* to the weight. Similarly, λ_{a^*} and λ_{b^*} are the parameters concerning Δa^* and Δb^*, respectively.

D. Modification by Consideration of Color Gamut

$\tilde{L}^*$ obtained by (1) is a tentative modified lightness because the color $(\tilde{L}^*, a^*, b^*)$ may be out from the color gamut. We need the modification so that the output colors are in the color gamut.

First, the modification for lightness is applied as follows:

$$\hat{L}^* = \begin{cases} 0, & \tilde{L}^* < 0, \\ \tilde{L}^*, & 0 \leq \tilde{L}^* \leq 100, \\ 100, & \text{otherwise}. \end{cases} \tag{10}$$

$(\hat{L}^*, a^*, b^*)$ may still out from the color gamut and in the case, the modification for a^* and b^* components are applied. The detail is same as our previous method [18].

III. Experimental Results

The effectiveness of our proposed method is confirmed through experiments. Here we use six images purposely designed to test color blindness (Fig. 4) in the experiment because it is easy to evaluate resulting images (color modification results). Figs. 5 and 6 show the same images observed by people with protanopia and deuteranopia, respectively. Both people with protanopia and those with deuteranopia cannot see the numbers or animals clearly.

A. Quantitative Evaluation

The quantitative evaluation method of the resulting images is defined here. The degree of improvement of the contrast between colors that are difficult to distinguish for dichromats is inspired by following Refs. [7] and [18]. Here protanopia and deuteranopia are referred to as K-type color vision, where K is replaced by P (protanopia) or D (deuteranopia) where necessary.

The index used V_{K} is defined as

$$V_{\mathrm{K}} = U_{\mathrm{K}}^{\mathrm{out}} / U_{\mathrm{K}}^{\mathrm{in}} \tag{11}$$

with

$$U_{\mathrm{K}}^{\mathrm{out}} = \sum_{(i,j)\in\sigma_{\rho'}} w_{ij} \left| \Delta E_{\mathrm{K},ij}^{\mathrm{out}} - \Delta E_{ij}^{\mathrm{in}} \right| \tag{12}$$

and

$$U_{\mathrm{K}}^{\mathrm{in}} = \sum_{(i,j)\in\sigma_{\rho'}} w_{ij} \left| \Delta E_{\mathrm{K},ij}^{\mathrm{in}} - \Delta E_{ij}^{\mathrm{in}} \right|, \tag{13}$$

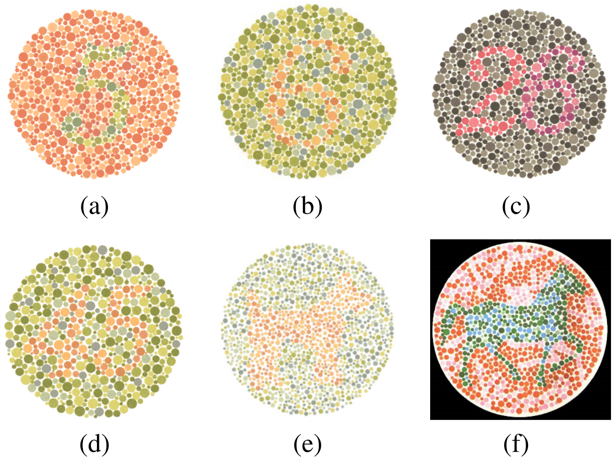


Fig. 4. Experimental images: (a) Chart 5, (b) Chart 6, (c) Chart 26, (d) Chart 45, (e) Dog, (f) Horse.

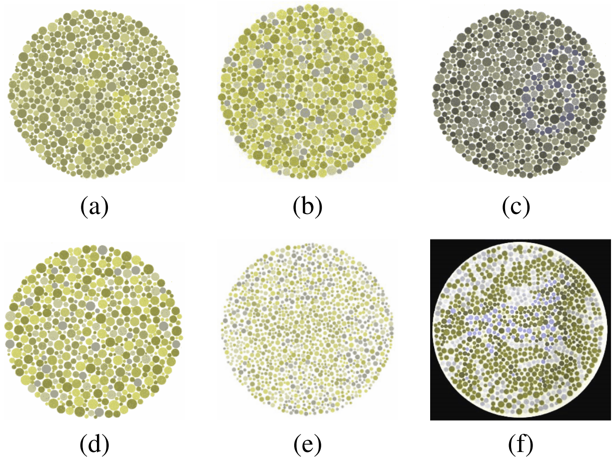


Fig. 5. Experimental images observed by person with protanopia: (a) Chart 5, (b) Chart 6, (c) Chart 26, (d) Chart 45, (e) Dog, (f) Horse.

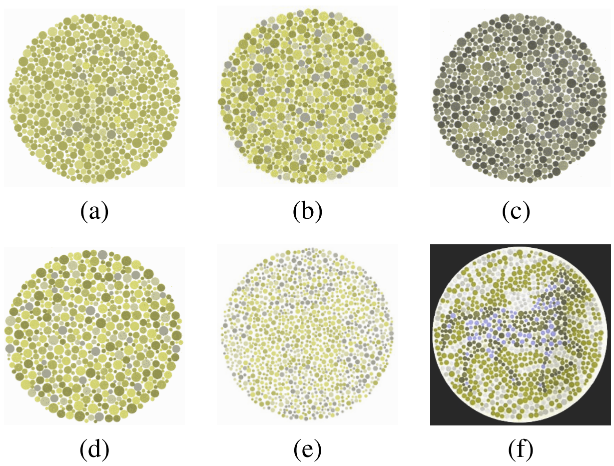


Fig. 6. Experimental images observed by person with deuteranopia: (a) Chart 5, (b) Chart 6, (c) Chart 26, (d) Chart 45, (e) Dog, (f) Horse.

where $\Delta E_{\mathrm{K},ij}^{\mathrm{out}}$ is the color difference between the ith and jth pixels in an output image perceived in K-type color vision. Its definition is as follows:

$$\Delta E^{\rm out}_{{\rm K},ij} = \left[(L^{*\rm out}_{{\rm K},i} - L^{*\rm out}_{{\rm K},j})^2 + (a^{*\rm out}_{{\rm K},i} - a^{*\rm out}_{{\rm K},j})^2 + (b^{*\rm out}_{{\rm K},i} - b^{*\rm out}_{{\rm K},j})^2\right]^{1/2}. \quad (14)$$

$L^{*\rm out}_{{\rm K},i}$ is the L^* component of the ith pixel of an output image perceived in K-type color vision. $\Delta E^{\rm in}_{{\rm K},ij}$ is similarly defined. $\Delta E^{\rm in}_{ij}$ is the color difference perceived by normal trichromats.

The color contrast for protanopes and deuteranopes becomes similar to those with normal color vision when $U_{\rm K}$ is close to 0. The contrast of an input color image for people with normal color vision is similar to that of the resulting color-converted image for people with K-type color vision and indiscriminable colors disappear when $U^{\rm out}_{\rm K}$ is close to 0. Therefore, it is preferable that $V_{\rm K}$ is close to 0. In (11), $U^{\rm out}_{\rm K}$ is normalized by $U^{\rm in}_{\rm K}$.

Same as Refs. [7] and [18], we only focus on the part which are difficult to distinguish for K-type people in the quantitative evaluation. This time we introduce the weight w_{ij} in (12) and (13) to realize it.

B. Parameter Setting

We set $\rho = 10$ which means that the size of the considered neighborhood is 21×21. For the parameter ϵ in the modification process considering the color gamut [18], we set it to $\epsilon = 0.1$ same as the Ref. [18]. For the parameter α, the contrast increases with as shown in Fig. 7. When α is too small, such as $\alpha = 5$ (Figs. 7(a) and 7(d)), the number in the image is difficult to distinguish. Thus in our experiment we set α to 15 to ensure sufficient contrast.

We refer to the Ref. [20] to determine parameters λ_{L^*}, λ_{b^*}, and λ_{a^*}. It can be said that at least ΔE should be larger than 2.3 to catch the small color difference between two colors [20]. Thus we set the parameters $\lambda_{L^*} = \lambda_{b^*} = 3$ so that people with protanopia or deuteranopia can notice the difference between two colors. On the other hand, when $\Delta E > 15$, difference of ΔE makes little sense for the human visual system [20]. Then λ_{a^*} is set as 15.

There is one parameter, ρ', involved in the computation of the index $V_{\rm K}$. We set $\rho' = 10$ because ρ is 10 in the lightness modification process. In addition, values of λ_{L^*}, λ_{b^*}, and λ_{a^*} of w_{ij} in (12) and (13) are also set as same values to the lightness modification process.

C. Experiment on Weighting

The results for Chart 5 and Chart 6 are described. Fig. 8 shows the lightness modification results obtained by the proposed method and simulated images observed by people with protanopia and deuteranopia. Figs. 8(b) and 8(f) show which part of these images that our weight is working on it. In Figs. 8(c), 8(d), 8(g), and 8(h), the numbers which are indistinguishable in input images by people with protanopia and deuteranopia can be clearly observed.

It is first necessary to ensure the effectiveness of our proposed weighting. To achieve this, we remove the weighting from the proposed method. The method without weighting is referred as the "comparative method" and the parameter setting of it is the same as that in the proposed method.

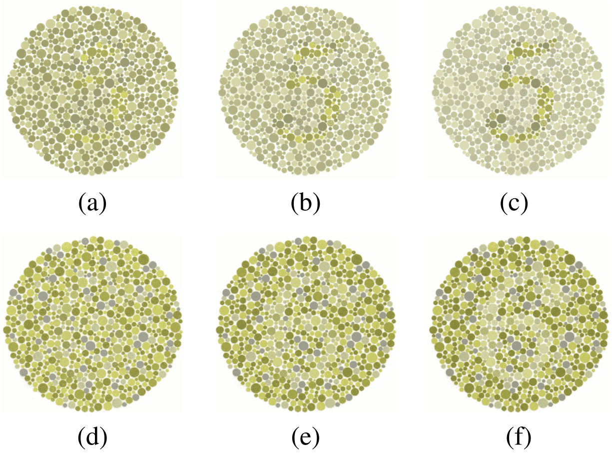


Fig. 7. Lightness modification results for Chart 5 ((a)–(c)) and Chart 6 ((d)–(f)) with different parameter α when $(\lambda^*_L, \lambda^*_b, \lambda^*_a) = (3, 3, 15)$ (observed by person with protanopia): (a) $\alpha = 5$, (b) $\alpha = 10$, (c) $\alpha = 15$, (d) $\alpha = 5$, (e) $\alpha = 10$, (f) $\alpha = 15$.

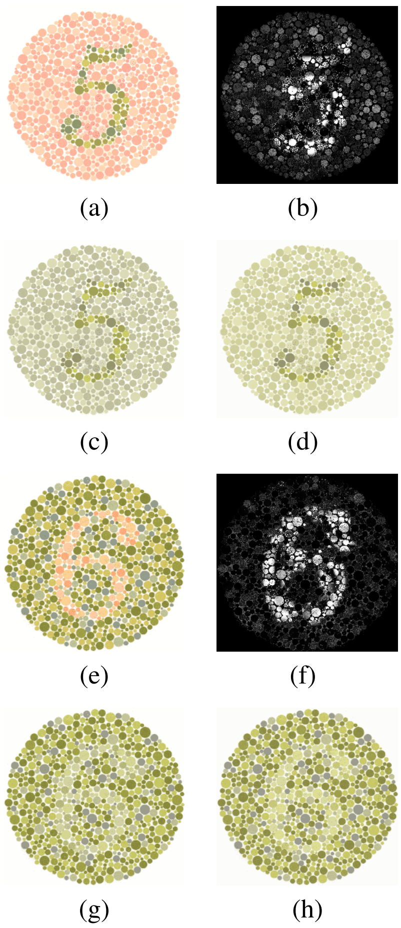


Fig. 8. Images with modified lightness obtained by the proposed method: (a) resulting image for Chart 5, (b) weighting image for Chart 5, (c) image in (a) observed by person with protanopia, (d) image in (a) observed by person with deuteranopia, (e) resulting image for Chart 6, (f) weighting image for Chart 6, (g) image in (e) observed by person with protanopia, (h) image in (e) observed by person with deuteranopia.

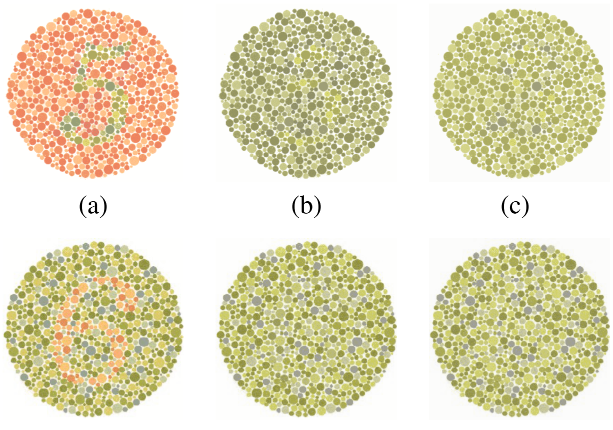


Fig. 9. Images with modified lightness obtained by the comparative method: (a) resulting image for Chart 5, (b) image in (a) observed by person with protanopia, (c) image in (a) observed by person with deuteranopia, (d) resulting image for Chart 6, (e) image in (d) observed by person with protanopia, (f) image in (d) observed by person with deuteranopia.

TABLE I
VALUES OF V_K FOR CHART 5 AND CHART 6.

Method	Chart 5		Chart 6	
	P	D	P	D
Proposed	0.61	0.61	0.51	0.47
Comparative method	1.03	0.98	1.00	0.97

TABLE II
PARAMETER SETTINGS OF EACH METHOD.

Method	Parameter setting
Takimoto	$\alpha = 0.5$, $\beta = 0.5$.
Milić	$k = 5$, $p_i - a_i = 5°$, $b_i - p_i = 5°$.
Tennenholtz	$\lambda = 100$, $m = 15$, $n = 15$.
Proposed	$\alpha = 15$, $\lambda_{L^*} = 3$, $\lambda_{b^*} = 3$, $\lambda_{a^*} = 15$, $\rho = 10$, $\epsilon = 0.1$.

TABLE III
VALUES OF V_P FOR MODIFIED IMAGES.

Image	Method			
	Takimoto	Milić	Tennenholtz	Proposed
Chart 5	0.98	0.71	0.58	0.61
Chart 6	0.92	1.43	1.12	0.51
Chart 26	0.83	1.01	0.96	0.81
Chart 45	0.72	1.39	1.41	0.43
Dog	0.98	1.17	0.92	0.50
Horse	0.94	1.47	1.17	0.74

TABLE IV
VALUES OF V_D FOR MODIFIED IMAGES.

Image	Method			
	Takimoto	Milić	Tennenholtz	Proposed
Chart 5	0.88	0.77	0.74	0.61
Chart 6	0.80	1.19	0.90	0.47
Chart 26	0.73	0.95	0.85	0.72
Chart 45	0.72	0.94	1.11	0.26
Dog	0.86	1.15	0.94	0.43
Horse	0.82	1.16	0.97	0.64

The lightness modification images for Chart 5 and Chart 6 obtained by the comparative method are shown in Fig. 9. Upon removing the weighting from the proposed method, numbers 5 and 6 cannot be observed by people with protanopia and deuteranopia as shown in Figs. 9(b), 9(c), 9(e) and 9(f). That proves the effectiveness of our new weighting.

Table I shows the values of V_K for Chart 5 and Chart 6. The values of V_K for the proposed method are smaller than those for the comparative method. This means that the proposed method appropriately converts the colors in the input images that are difficult to distinguish for K-type color vision. In addition, the values of V_K correspond to the subjective impression. For example, for the color conversion of Chart 5 and P-type color vision, the proposed method (Fig. 8(c)) has better contrast of the number 5 than the comparative method (Fig. 9(b)), according to our subjective evaluation, consistent with the values in Table I.

D. Comparative Experiments

Here we choose three existing methods for comparison: Takimoto's method [11], which is an extension of Tanaka's method [7] and is a lightness modification method; Tennenholtz's method [15], which is also a lightness modification method; and Milić's method [13] as a recoloring method. The parameter settings of these three methods are given in Table II. In Takimoto's method, although color quantization is performed to reduce the calculate on time, it is omitted here to ensure sufficient image quality. In Takimoto's method, the contrast increases with α and β but with the naturalness decreases. For Takimoto's method we chose $\alpha = 0.5$ and $\beta = 0.5$ to maximize the contrast, as in our comparative experiment. The parameter setting of Milić's method is same as in Ref. [13]. For Tennenholtz's method, the values of the parameters used in Ref. [15] is unclear, so according to the optimization function we choose appropriate parameters and $f^{(2)}$ in Ref. [15] as the enhancement algorithm.

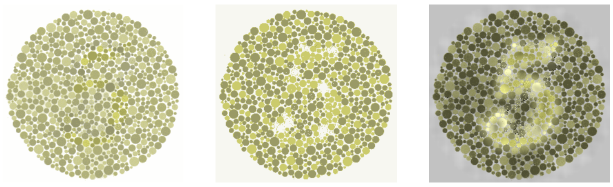
Tables III and IV show the values of V_K for the output images obtained by each method. Figs. 10–12 show some of the modified images obtained by the existing methods and the proposed method as observed by a person with protanopia.

As can be seen in Figs. 8(c) and 10(c) both the proposed method and Tennenholtz's method give high visibility of the number 5. The corresponding evaluation indices also have small values. No number can be seen in the image modified by Takimoto's method. Milić's method has less contrast than the proposed method.

In Fig. 11, although the number 45 can be seen in both the proposed method and Tennenholtz's method, the contrast of Tennenholtz's method is over worked and the proposed method having a smaller evaluation index. The number cannot be confirm in the resulting image obtained by Milić's method and Takimoto's method has much less contrast than proposed method.

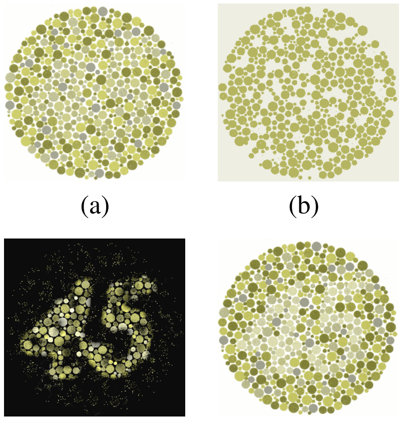
As shown in Fig. 12, the dog is clearly visible in the image modified by our proposed method. For Tennenholtz's method, only the contour of the dog can be seen, and no dog can be seen for the other two methods.

Similar results were basically obtained for other images. These experimental results show the validity of the proposed method.



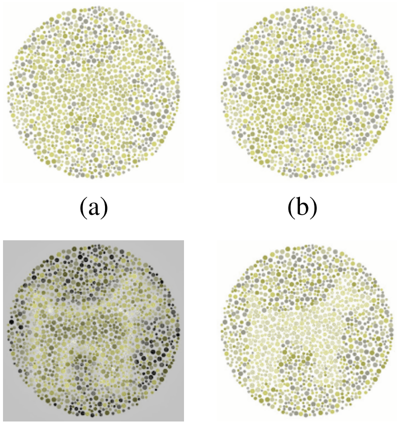
(a) (b) (c)

Fig. 10. Modified images observed by person with protanopia for each method: (a) Takimoto, (b) Milić, (c) Tennenholtz.



(a) (b) (c) (d)

Fig. 11. Modified images observed by person with protanopia for each method: (a) Takimoto, (b) Milić, (c) Tennenholtz, (d) proposed method.



(a) (b) (c) (d)

Fig. 12. Modified images observed by person with protanopia for each method: (a) Takimoto, (b) Milić, (c) Tennenholtz, (d) proposed method.

IV. Conclusions

In this paper, we proposed a new method that yields barrier-free color images for protanopes and deuteranopes. Our proposed method modifies the lightness components of an image to preserve its visual detail. As a result of defining a new weighting, our proposed method is more effective than existing methods. The validity of the method was shown subjectively and quantitatively through experiments. Using color blindness test images is to ensure a clear comparison. However, natural images have more complex colors, and our future aim is to improve the proposed method to increase the clarity of the colors in such images for people with visual impairments.

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