Information Preserving Color Transformation for Protanopia and Deuteranopia

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***Abstract*—In this letter, we proposed a new recoloring method for people with protanopic and deuteranopic color deficiencies. We present a color transformation that aims to preserve the color information in the original images while maintaining the recolored images as natural as possible. Two error functions are introduced and combined together to form an objective function using the Lagrange multiplier with a user-specified parameter λ. This objective function is then minimized to obtain the optimal settings. Experimental results show that the proposed method can yield more comprehensible images for color-deficient viewers while maintaining the naturalness of the recolored images for standard viewers.**

***Index Terms*—Color deficiency, image processing, Lagrange multiplier, recoloring.**

I. INTRODUCTION

DUE to the increasing use of colors in multimedia contents to convey visual information, it becomes more important to perceive colors for information interpretation. However, roughly around 5%–8% of men and 0.8% of women have certain kinds of color deficiency. Unlike people with normal color vision, people with color deficiency have difficulties discriminating certain color combinations and color differences. Hence, multimedia contents with rich colors, which can be well discriminated by people with normal color vision, may sometimes cause misunderstanding to people with anomalous color vision.

Humans' color vision is based on the responses to photons in three different types of photoreceptors, which are named "cones" and are contained in the retina of human eyes [1]. The peak sensitivities of these three distinct cones lie in the long-Wavelength (L), middle-wavelength (M), and short-wavelength (S) regions of the spectrum. Anomalous trichromacy is frequently characterized by a shift of one or more cone types so that the pigments in one type of cone are not sufficiently distinct from the pigments in others. For example, L-Cones are more like M-Cones in protanomaly and M-Ccones are more like L-Cones in deuteranomaly. On the other hand, dichromats have only two distinct pigments in the cones and entirely lack one of the three cone types. Lack of L-cones is referred to as protanopia, lack of M-cones is referred to as deuteranopia, and lack of S-cones is referred to as tritanopia. Among these three types of dichromats, protanopia and deuteranopia have difficulty in distinguishing red from green, while tritanopia has difficulty in discriminating blue from yellow. So far, many research works have been conducted on simulating color-deficient vision [2]–[5]. These approaches represent color stimuli as vectors in the three-dimensional LMS space, where three orthogonal axes L, M, and S represent the quantum catch for each of the three distinct cone types. Since the dichromatic vision is the reduced form of trichromatic vision, the lack of one cone type can be simulated by collapsing one of the three dimensions into a constant value.

To enhance the comprehensibility of images for color-deficient viewers, daltonization is proposed in [6] to recolor images for dichromats. In [6], the authors first increase the red/green contrast in the image and then use the red/green contrast information to adjust brightness and blue/yellow contrast. In [7], Ishikawa *et al.* described the manipulation of webpage colors for color-deficient viewers. They first decompose a webpage into a hierarchy of colored regions and determine "important" pairs of colors that are to be modified. An objective function is then defined to maintain the distances of these color pairs, as well as to minimize the extent of color remapping. This approach is further extended to deal with full-color images in [8]. On the other hand, Seuttgi Ymg *et al.* [9] proposed a method to modify colors for dichromats and anomalous trichromats. For dichromats, a monochromatic hue is changed into another hue with less saturation, while for anomalous trichromats, the proposed method tends to keep the original colors. In [10], Rasche *et al.* use a linear transform to convert colors in the CIELAB color space and enforce proportional color differences during the remapping. Based on the same constraint for color deficiency, the authors further improve the optimization process by using the majorization method [11].

Basically, all the aforementioned works may generate images that are more comprehensible to color-deficient viewers. However, recolored images may look very unnatural to viewers with normal vision. From an application viewpoint, images in a public place may be simultaneously observed by normal people and color-deficient people. For example, in a public transportation system, many advertisements and traffic maps are delivered in colors. Without concerning the needs of deficient observers, color-deficient people may have difficulty in understanding the image contents. On the contrary, if only concerning the needs of color-deficient people, then these recolored images may look annoying to normal observers. Hence, in this letter, we aim to develop a recoloring algorithm that can automatically construct a transformation to maintain details for color-deficient viewers while preserving naturalness for standard viewers.

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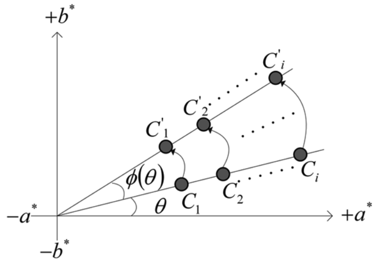
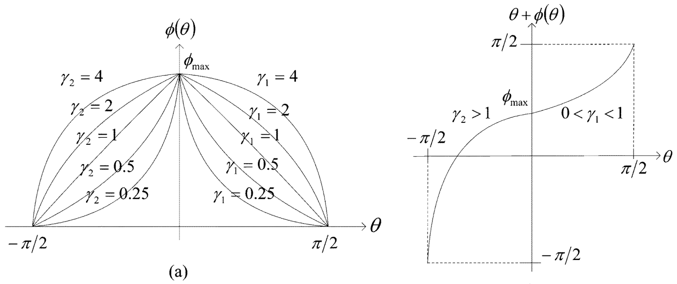


Fig. 1. Rotation operation in the a^*–b^* plane.



(a)

(b)

Fig. 2. (a) Function $\phi(\theta)$ with three parameters: $\phi_{\max}$, γ_1,, and γ_2. (b) Function $\theta + \phi(\theta)$ with parameters $\phi_{\max}$, γ_1, and γ_2 for a half plane.

II. Color Reproduction for Protanopia and Deuteranopia

A. *Color Reproduction Method*

In this letter, we focus on protanopia and deuteranopia, which are the major types of color deficiency. In order to mimic the color perception of protanopia and deuteranopia, we adopt Brettel's algorithm [2] to simulate the perceived images. Here, we adopt CIELAB color space as the working domain. In both protanopia and deuteranopia, there is strong correlation between the original colors and the simulated colors in the values of L* and b*, while there is a weak correlation between the original a* and the perceived a*. That is, the original color information in a* gets lost significantly. To retain the information in a*, a reasonable way is to do some kind of image warping so that the information of a* is mapped onto the b* axis in the CIELAB color space.

In our approach, we aim to maintain the color differences of color pairs in the CIELAB color space while keeping the recolored images as natural as possible. To keep the recolored image natural, three premises are adopted. First, the recolored image has the same luminance as the original image. Second, colors with the same hue in the original image still have the same hue after recoloring. Third, the saturation of the original colors is not altered after recoloring. In our approach, a rotation operation is adopted in the a*–b* plane to transform the information of a* onto the b* axis, as illustrated in Fig. 1. Here, we assume some color stimuli $\mathrm{C_1, C_2, \ldots, C_i}$ have the same included angle θ with respect to the a* axis. The rotation operation maps these colors to new colors $\mathrm{C'_1, C'_2, \ldots, C'_i}$, which lay on another line with the included angle $\theta + \phi(\theta)$. If ignoring the nonlinear property of the iso-hue curves in the CIELAB color space [13], this rotation process simultaneously changes the hue of $\mathrm{C_1, C_2, \ldots, C_i}$ with the same amount of hue. Hence, the transformed colors $\mathrm{C'_1, C'_2, \ldots, C'_i}$ still share the same hue after color transformation. Moreover, the saturation of the original color $\mathrm{C_i}$ is also preserved.

In mathematics, this rotation operation can be formulated as a matrix multiplication. That is, we have

$$\begin{bmatrix} L' \\ a' \\ b' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi(\theta)) & -\sin(\phi(\theta)) \\ 0 & \sin(\phi(\theta)) & \cos(\phi(\theta)) \end{bmatrix} \begin{bmatrix} L \\ a \\ b \end{bmatrix} \qquad (1)$$

where $\mathrm{(L', a', b')}$ and $\mathrm{(L, a, b)}$ are the CIELAB values of the recolored color and the original color, respectively. $\phi(\theta)$ is a monotonically decreasing function of θ. Since the color difference along the b* axis can be well discriminated by protanopic and deuteranopic viewers, $\phi(\theta))$ decreases to zero when θ approaches $\pm\pi/2$. In this letter, we define $\phi(\theta)$ to be

$$\phi(\theta) = \phi_{\max}\left[1 - \left(\frac{|\theta|}{\pi/2}\right)^{\gamma}\right] \qquad (2)$$

for the right half-plane of the a*–b* plane, where θ ranges from $-\pi/2$ to $+\pi/2$. Here, $\phi_{\max}$ represents the maximal change of the included angle and γ represents the degree of the decreasing rate. These two parameters will be specified by optimizing an objective function based on the contents of the original color image. For the left half-plane $\pi/2 \le \theta \le 3\pi/2$, we define the $\phi(\theta)$ function in a similar manner but with different $\phi_{\max}$ and γ. This is because in practice, we may want the right half and the left half of the a*–b* plane to have different transformations, as shown in Fig. 2(a). Moreover, since $\phi(\theta)$ approaches zero when colors are close to the b* axis, crossover of colors can be avoided when crossing the b* axis.

In Fig. 2(b), we show the plot of the transformed hue $\theta + \phi(\theta)$ versus the original hue θ for the right-half a*–b* plane. If the $\phi_{\max}$ is positive, then the quadrant with positive $\mathrm{b}^*(0 \leqslant \theta \leqslant \pi/2)$ will be compressed while the quadrant with negative $b^*(-\pi/2 \leqslant \theta < 0)$ will be expanded and vice versa. To avoid colors crossover in the compressed quadrant, we require

$$\frac{d(\theta + \phi(\theta))}{d\theta} \ge 0. \qquad (3)$$

By combining (2) and (3), we have

$$\phi_{\max}\gamma \le \frac{(\pi/2)^{\gamma}}{|\theta_1|^{\gamma-1}}. \qquad (4)$$

Since θ_1 ranges from $-\pi/2$ to $+\pi/2$, the LHS of (4) has the lower bound $\pi/2$. Thus, we can obtain the constraint $\phi_{\max}\gamma \leqslant \pi/2$. On the other hand, the constraint in (4) is not necessary in the expanded quadrant. Hence, we introduce two parameters γ_1 and γ_2, one for each quadrant. For the compressed quadrant, the constraint in (4) is required, while for the expanded region, no constraint is needed for $\phi_{\max}$ and γ. In the proposed algorithm, there would be six parameters in total. Their notations and meanings are listed in Table I.

B. *Optimization Using Detail and Naturalness Criteria*

In this section, we introduce two criteria, one for detail preserving and the other for naturalness preserving. For each color

TABLE I
PARAMETERS FOR RECOLORING

ϕ_{Rmax}	the maximal change of the included angle in the right plane
ϕ_{Lmax}	the maximal change of the included angle in the left plane
γ_{R1}	the degree of the decreasing rate in the upper-right plane
γ_{R2}	the degree of the decreasing rate in the lower -right plane
γ_{L1}	the degree of the decreasing rate in the upper-left plane
γ_{L2}	the degree of the decreasing rate in the lower-left plane

pair in the original color domain, we first calculate the perceived color difference with respect to a person with normal vision. Then, for the corresponding color pair in the transformed color domain, we calculate the perceived color difference with respect to a person with protanopic or deuteranopic deficiencies. As mentioned above, we follow Brettel's algorithm [2] to simulate the color perception for protanopia and deuteranopia. In our criterion, we wish these two perceived color differences to be as similar as possible. Hence, we define an error function to be

$$E_{\text{detail}} = \sum_i \sum_j (|C_i - C_j| - |\text{SIM}(T(C_i)) - \text{SIM}(T(C_j))|)^2 \qquad (5)$$

where i and j range over the colors contained in the images, $|\cdot|$ is a perceptual color difference metric, $\text{T}(\cdot)$ is our recoloring function, and $\text{SIM}(\cdot)$ denotes the simulated color perception using Brettle's algorithm. By minimizing this error function, we can preserve color details of the original image.

On the other hand, we attempt not to dramatically modify the color perception of the color images since a severe modification may make the recolored image extremely unnatural for normal viewers. Hence, we define another error function to be

$$E_{\text{naturalness}} = \sum_i (\|C_i - T(C_i)\|)^2 \qquad (6)$$

where i ranges over all the colors in the original color image. Minimizing this error function shortens the color distance between the original colors and the corresponding remapped colors. To preserve both details and naturalness, we combine these two error functions using the Lagrange multiplier with a user-specified parameter λ. Here, we further normalize these two error functions by their arithmetic means to achieve similar order of magnitude. That is, the total error is written as

$$E_{\text{total}} = \overline{E_{\text{detail}}} + \lambda \overline{E_{\text{naturalness}}}. \qquad (7)$$

To minimize the objective function in (7), we roughly estimate $\phi_{\text{R max}}$ and $\phi_{\text{L max}}$ in the initialization stage with $\gamma_{R1}, \gamma_{R2}, \gamma_{L1}$, and γ_{L2} fixed to 1. Then we use the Fletcher–Reeves conjugate-gradient method with the constraint in (4) to obtain the optimal solution. By choosing different values of λ, users may adjust the tradeoff between details and naturalness. A larger λ makes the recolored image more natural for normal viewers, while a smaller λ makes the recolored image more comprehensible for color-deficient viewers.

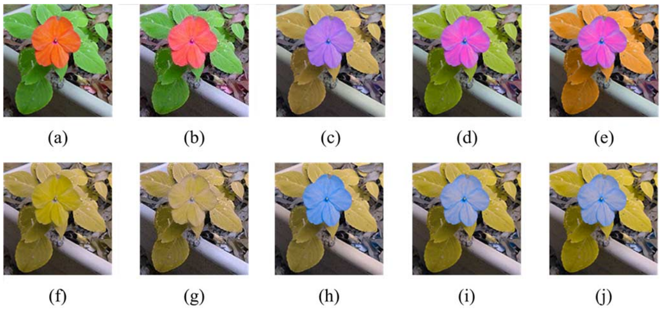


Fig. 3. (a) Original image. (b) Recolored by the Daltonization method with a middle-level correction [6]. (c) Recolored by Rasche's method [10]. (d) Recolored by our proposed method with $\lambda = 0.1$. (e) Recolored by our proposed method with $\lambda = 0$. (f)–(j): Corresponding color images perceived by people with deuteranopic color deficiency.

One more thing to mention is about the nonlinear property of the iso-hue curves in the CIELAB color space [13]. That is, two colors with the same included angle θ in the a^*–b^* plane may not have the same value of hue. Due to this nonlinear property, colors with the same hue in the original image may generate colors with different hues in the recolored image. To solve this problem, we may simply apply the hue-linearization process mentioned in [14] as a preprocessing and then apply the delinearization process after the recoloring algorithm.

III. EXPERIMENTAL RESULTS

In Fig. 3, we demonstrate some experimental results for the "flower" image. Fig. 3(a)–(e) shows the images perceived by normal viewers, while Fig. 3(f)–(j) presents the images perceived by viewers with deuteranopic deficiency. We can observe that the color contrast between the red flower and the green leaves is lost for people with deuteranopic deficiency. We compare our method with the Daltonization method [6] and Rasche's method [10], as shown in Fig. 3(b)–(e) and (g)–(j). We may observe that even though the Daltonization method with a middle-level correction may also preserve the naturalness of the recolored image for normal people, the contrast between the flower and leaves looks very poor for deuteranopic people. On the other hand, even though Rasche's method may create great contrast for deuteranopic people, the naturalness of the recolored image is extremely poor for people with normal vision. In comparison, our method may well preserve both details and naturalness at the same time.

To verify the effect of λ, we also demonstrate in Fig. 3(e) that our proposed method will produce an extremely unnatural recolored image if $\lambda = 0$. Furthermore, in Table II, we compare the naturalness error and detail error among different methods, based on (5) and (6). In our approach, the naturalness error decreases while detail error increases when λ rises. For the Daltonization method, even though its naturalness error is less than ours, its detail error becomes extremely high. On the other hand, even though Rasche's method has a smaller detail error, its naturalness error is larger. These experimental results show that both naturalness and detail can be properly preserved by our method.

TABLE II
COMPARISON OF NATURALNESS ERROR AND DETAIL ERROR

	Original image	Daltonization [6]	Rasche's method [10]	Proposed method (λ=0)	Proposed method (λ=0.05)	Proposed method (λ=0.1)
$E_{naturalness}$	**0**	**306**	**2314**	**2679**	**1705**	**1510**
E_{detail}	**560**	**796**	**193**	**212**	**220**	**234**


(a) (b) (c)
(d) (e) (f)

Fig. 4. (a) Original image. (b) Perceived image by protanopic viewer. (c) Perceived image by deuteranopic viewer. (d) Recolored image for protanopia. (e) Perceived image of (d) by protanopic viewers. (f) Recolored image for deuterangopia. (g) Perceived image of (f) by deuteranopic viewers.

In Fig. 4, we show more examples to verify the effectiveness of the proposed method.

We also used Thurstone's Law of Comparative Judgment [12] for subjective evaluation. In our subjective experiments, ten participants with normal vision were involved and six representative color images were chosen, as shown in Fig. 5. All ten participants were graduate students with some background in video coding and image processing. Since we have difficulty in finding color-deficient viewers, we adopted Brettel's algorithm [2] to mimic the perception of protanopia and deuteranopia. In the first experiment, each of the six images was, respectively, recolored by the Daltonization method, Rasche's method, and our method with $\lambda = 0.1$. For each image, the original image was first shown to the participants. Then, exhaustive paired comparisons were performed over the recolored images, and the participants were asked to choose the more natural image from each pair. This experiment is to evaluate the naturalness of the recolored images from the viewpoint of normal viewers. In the second experiment, Brettel's algorithm was applied over the original images and recolored images to simulate the perceived images for deuteranopia. Exhaustive paired comparisons were performed again over the simulated images, and the participants were asked to choose the more comprehensible image from each pair. This experiment is to evaluate the comprehensibility of the recolored images from the viewpoint of deuteranopic viewers. The results of these two subjective experiments were analyzed based on Thurstone's Law of Comparative Judgment [12]. The scaling of data is shown in Fig. 6. Fig. 7(a) indicates that both our method and the Daltonization method produce more natural images, while Fig. 7(b) indicates that our method may preserve more details than the other two methods.

Fig. 5. Six images for the subjective evaluation.

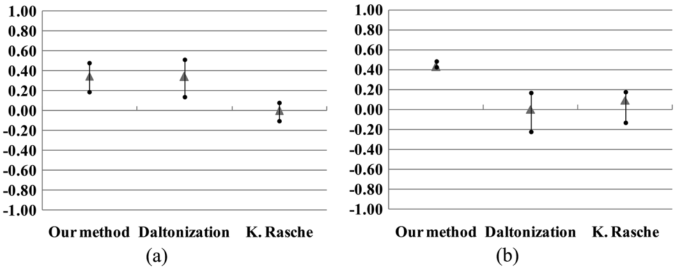


Fig. 6. Experimental results. (a) Scales from the "naturalness" experiment. (b) Scales from the "comprehensibility" experiment.

IV. CONCLUSION

We have presented in this letter a new recoloring method for people with protanopic or deuteranopic deficiency. We propose a color transformation that can yield more comprehensible images for protanopic or deuteranopic viewers while maintaining the naturalness of the recolored images for standard viewers. The same procedure can be extended to the case of tritanopia, in which blue and yellow tones cannot be well distinguished. The experimental results show that our proposed method performs subjectively better than others, in terms of comprehensibility and naturalness.

REFERENCES

[1] Wandell, *Foundations of Vision*. Sunderland, MA: Sinauer, 1995.

[2] H. Brettel, F. Vi'enot, and J. Mollon, "Computerized simulation of color appearance for dichromats," *J. Optic. Soc. Amer. A*, vol. 14, no. 10, pp. 2647–2655, Oct. 1997.

[3] G. Meyer and D. Greenberg, "Color-defective vision and computer graphics displays," *IEEE Comput. Graph. Appl.*, vol. 8, no. 5, pp. 28–40, Sep. 1988.

[4] S. Kondo, "A computer simulation of anomalous color vision," in *Color Vision Deficiencies*. Amsterdam, The Netherlands: Kugler & Ghedini, 1990, pp. 145–159.

[5] J. Walraven and J. W. Alferdinck, "Color displays for the color blind," in *Proc. IS&T/SID 5th Color Imaging Conf.*, 1997, pp. 17–22.

[6] R. Dougherty and A. Wade, *Daltonize*. [Online]. Available: http://www.vischeck.com/daltonize/.

[7] M. Ichikawa, K. Tanaka, S. Kondo, K. Hiroshima, K. Ichikawa, S. Tanabe, and K. Fukami, "Web-page color modification for barrier-free color vision with genetic algorithm," *Lecture Notes Comput. Sci.*, vol. 2724, pp. 2134–2146, 2003.

[8] M. Ichikawa, K. Tanaka, S. Kondo, K. Hiroshima, K. Ichikawa, S. Tanabe, and K. Fukami, "Preliminary study on color modification for still images to realize barrier-free color vision," in *Proc. IEEE Int. Conf. Systems, Man, Cybernetics*, 2004, pp. 36–41.

[9] S. Yang and Y. M. Ro, "Visual contents adaptation for color vision deficiency," in *Proc. IEEE Int. Conf. Image Process.*, Sep. 2003, vol. 1, pp. 453–456.

[10] K. Rasche, R. Geist, and J. Westall, "Detail preserving reproduction of color images for monochromats and dichromats," *IEEE Comput. Graph. Appl.*, vol. 25, no. 3, pp. 22–30, May–Jun. 2005.

[11] K. Rasche, R. Geist, and J. Westall, "Re-coloring images for gamuts of lower dimension," *EuroGraphics*, vol. 24, no. 3, pp. 423–432, 2005.

[12] W. S. Torgerson, *Theory and Method of Scaling*. New York: Wiley, 1967.

[13] G. Hoffmann, *CIELab Color Space*. [Online]. Available: http://www.fho-emden.de/~hoffmann/cielab03022003.pdf.

[14] G. J. Braun, F. Ebner, and M. D. Fairchild, "Color Gamut mapping in a hue-linearized CIELab color space," in *Proc. IS&T/SID6th Color Imaging Conf.*, 1998, pp. 163–168.