EXTENDING THE VISIBILITY OF DICHROMATS USING HISTOGRAM EQUALIZATION OF HUE VALUE DEFINED FOR DICHROMATS

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Dichromats lacks one of the three cone cells, which detects red, green, and blue lights. For example, red-green color blinds cannot distinguish the color between red, yellow, and green. In order to extend the ability of dichromats to recognize the color difference, we proposed a method to expand the color difference when observed by dichromats. We have defined a hue variable for dichromats and implemented to our algorithm. We applied the histogram equalization to the hue of dichromats in order to enlarge the color difference recognized by dichromats. We have applied our method to RGB color image, and shown its performance at the experimental section.

Keywords: Histogram equalization; hue; dichromat; color blind.

1. Introduction

Human eye potentially has three kinds of cone cells. On the other hand, dichromats lacks one of the cell. For example, 8% males of Northern European descent are affected red-green color blindness. In this paper, we propose a method to enhance the visibility of dichromats.

Enhancing the visibility of color image for dichromats is an important research field. In recent years, many researchers[1,2,3,4,7,6,5,9,10,13,14,15,17,19,20,21,22,24,25] are still struggling with this hot topic, and there is still a lot of room for further improvement in this ongoing research topic.

For example, Rasche et al.[18] transformed the color space with homographic projection so that the color difference of dichromats becomes similar to that of

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trichromats. Nakauchi and Onouchi[16] applied a clustering algorithm in color space and they stretched the color difference so that each cluster becomes far apart. Kuhn et al.[12] employed spring-mass model in order to make the color difference of dichromats to be as same as that of trichromats. Tanaka et al.[23] gave a closed-form solution to the cost function where the color difference between neighboring pixels becomes similar to a certain value which is calculated from the color difference of neighboring pixels under trichromatic view.

Our approach is different from existing methods. We define the hue barometer of dichromats. Some of existing methods use hue value in their algorithm, however, all of the hue values used are those of the trichromats. Those methods do not use the hue value designed for dichromats. We define a hue for dichromats which has one-to-one correspondance to the L*a*b* hue of trichromats. Using our hue value, we propose a method to enhance the visibility of the image when looked by dichromats.

Our method applies the histogram equalization to the hue of dichromats so that the color can be distiguishable for them. Hue histogram equalization stretches the contrast of the hue. Huang et al.[8] also applied the histogram equalization to improve the visibility of dichromats. However, they used the hue of HSV color space for trichromats. On the other hand, we use the hue defined for dichromats. Stretching the contrast of such hue enables to increase the visibility of color image when observed by dichromats.

2. Color enhancement

2.1. *Hue for dichromats*

The color value which dichromats perceive can be calculated as follows. RGB value is first converted to CIE-XYZ value, and after that it is converted to LMS value. LMS represents the sensitivity of cone cells. Judd[11] has shown how to calculate the LMS values of dichromats. The conversion formula for protanopia is shown below.

$$\begin{pmatrix} L_p \\ M_p \\ S_p \end{pmatrix} = \begin{pmatrix} 0.0 & 2.02 & -2.52 \\ 0.0 & 1.0 & 0.0 \\ 0.0 & 0.0 & 1.0 \end{pmatrix} \begin{pmatrix} L \\ M \\ S \end{pmatrix} \tag{1}$$

And, the conversion formula for deuteranopia is shown below.

$$\begin{pmatrix} L_d \\ M_d \\ S_d \end{pmatrix} = \begin{pmatrix} 1.0 & 0.0 & 0.0 \\ 0.49 & 0.0 & 1.25 \\ 0.0 & 0.0 & 1.0 \end{pmatrix} \begin{pmatrix} L \\ M \\ S \end{pmatrix} \tag{2}$$

In xy-diagram calcualted from CIE-XYZ value, the white color is placed in $(x, y) = (0.33, 0.33)$ for trichromats. In this paper, we define the hue α of trichromats as an angle defined in xy-plane (Figure 1 (a)). The trichromatic hue α is defined as an angle around the white point $(x, y) = (0.33, 0.33)$. We define the $0°$ of α to be the direction of $-45°$. The hue angle α of a certain color (x, y) is calculated as
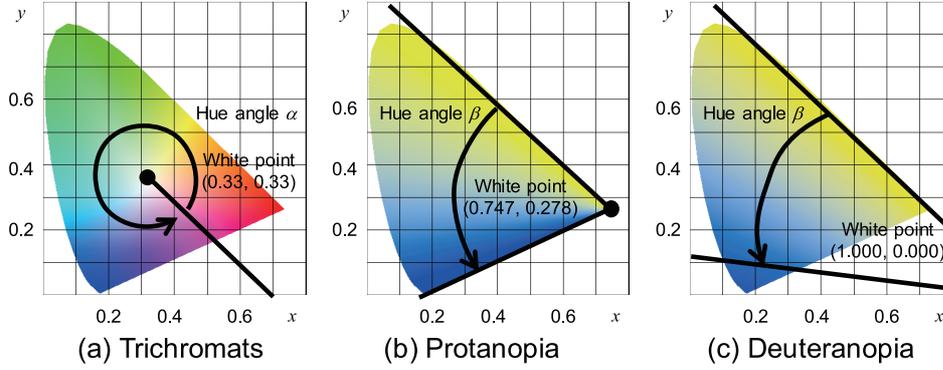
Fig. 1. Definition of hue of (a) trichromats, (b) protanopia, and (c) deuteranopia.

follows.

$$\alpha = \frac{\pi}{4} + \tan^{-1} \frac{y - 0.33}{x - 0.33} \, . \tag{3}$$

We also define the hue β of dichromats (Figure 1 (b)–(c)). Our definition of hue is mathematically convincing. Following Judd[11], the white point of protanopia is $(x, y) = (0.747, 0.253)$ and that of deuteranopia is $(x, y) = (1.000, 0.000)$. We define the hue β rotating around these white points, where it ranges from $140°$ direction to $200°$ direction for protanopia and ranges from $140°$ direction to $170°$ direction for deuteranopia. The angles of these ranges are carefully chosen so that the defined hue distributes inside the color gamut. The hue angle β of protanopia is calculated as follows.

$$\beta = \frac{\pi}{180} \left(140 + \frac{\alpha}{2\pi}(200 - 140) \right) , \tag{4}$$

and the hue angle β of deuteranopia is calcuted as follows.

$$\beta = \frac{\pi}{180} \left(140 + \frac{\alpha}{2\pi}(170 - 140) \right) . \tag{5}$$

Here, the hue angle α supposed to be from 0 to 2π.

Our defition of hue has strong relation with the L*a*b* hue of trichromats. The hue angle γ in L*a*b* space is defined as follows.

$$\gamma = \tan^{-1} \frac{b*}{a*} \, . \tag{6}$$

The relationship between our hue and L*a*b* hue is shown in Figure 2 (b). The horizontal axis of Figure 2 represents L*a*b* hue and the vertical axis of Figure 2 represents our hue. Figure 2 (b) shows the one-to-one correspondance between our hue when observed by dichromats and L*a*b* hue when observed by trichromats. Figure 2 (a) shows the relationship between L*a*b* hue and HSV hue when observed by dichromats. Figure 2 (a) has flat correspondance at yellow area and blue

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(a) HSV hue angle   (b) Our hue angle
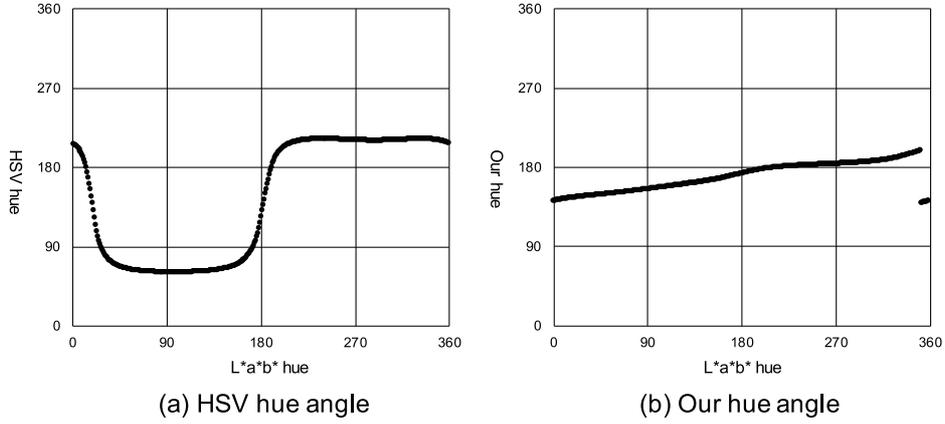
Fig. 2. Relation between L*a*b* hue and dichromats' hue [horizontal axis: L*a*b* hue angle of normal vision] [vertical axis: (a) HSV hue angle when observed by protanopia, and (b) our hue angle desinged for protanopia].

area, which results in multiple-to-one correspondance. Figure 2 shows the case for protanopia, while we skip the case for deuteranopia since it is almost the same.

2.2. *Image enhancement*

Using the hue defined in Section 2.1, the performace of the visibility enhancement for dichromats increases. We apply the histrogram equalization to the hue of dichromats; not the hue of trichromats such as HSV.

First, we create the cumulative histogram of α. Using this cumulative histogram, we converted the angle α to the angle β (Figure 3).

The calculation of hue is perfomed in xy-diagram which represent the chromaticity. The chromaticity (x, y) is calculated as follows.

$$x = \frac{X}{X + Y + Z}, \quad y = \frac{Y}{X + Y + Z}. \tag{7}$$

We calculate Equation (7) before applying our algorithm. Our algorithm modifies the chromaticity (x, y). After that, we multiply the scale $X + Y + Z$ to the obtained chromaticity (x, y) in order to obtain the CIE-XYZ value. Our algorithm does not require any parameters to be tuned (except the range of the hue angle).

3. Experimental result

3.1. *Quantitative evaluation*

First of all, we perform a numerical evaluation. Input image is shown in Figure 4 (a), which is consisted of 9 patches with different colors. Deuteranopia perceive this
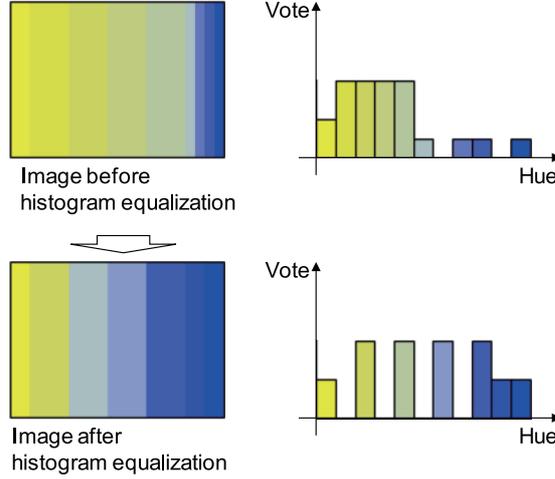
Fig. 3. Histogram equalization of dichromatic hue.

image as Figure 4 (b). The result of Huang[8] is shown in Figure 4 (c), and that of ours is shown in Figure 4 (d). Note that the color variation of patches in Figure 4 (d) has high correlation with that in Figure 4 (a).

Figure 5 shows the a*b* value of 9 patches. Note that the smoothly changing color of our method shown in Figure 5 (d).

When ignoring the brightness L*, the color difference between two L*a*b* values is defined as follows.

$$\Delta = \sqrt{(a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}\,. \tag{8}$$

Let us denote 9 patches in Figure 4 as #1, #2, ..., #9, from left to right, respectively. Table 1 shows the color difference between neighboring pairs, #1 and #2, #2 and #3, ... #8 and #9.

Table 1 shows that our color difference of dichromats has high correlation with the color difference of trichromats. Pearson correlation coefficient is commonly used to numerically represent the correlation. Pearson correlation coefficient is valid only for linear correlation, on the other hand, Spearman's rank correlation coefficient is adequate to represent the non-linear correlation. We calculate Spearman's rank correlation coefficient between two columns of Table 1; namely, the size of each sample is 8. The coefficient between the input data and our result is 0.976. Since the maximum of the coefficient is 1, the correlation of our result can be said as extremely high. The coefficient of Huang[8] is 0.333, and that of dichromats' perception is 0.381. Through this numerical evaluation, we proved that our method produces a color image whose color difference is similar to the perception of normal vision.

Here, we show the result of deuteranopia and we skip to show the result of

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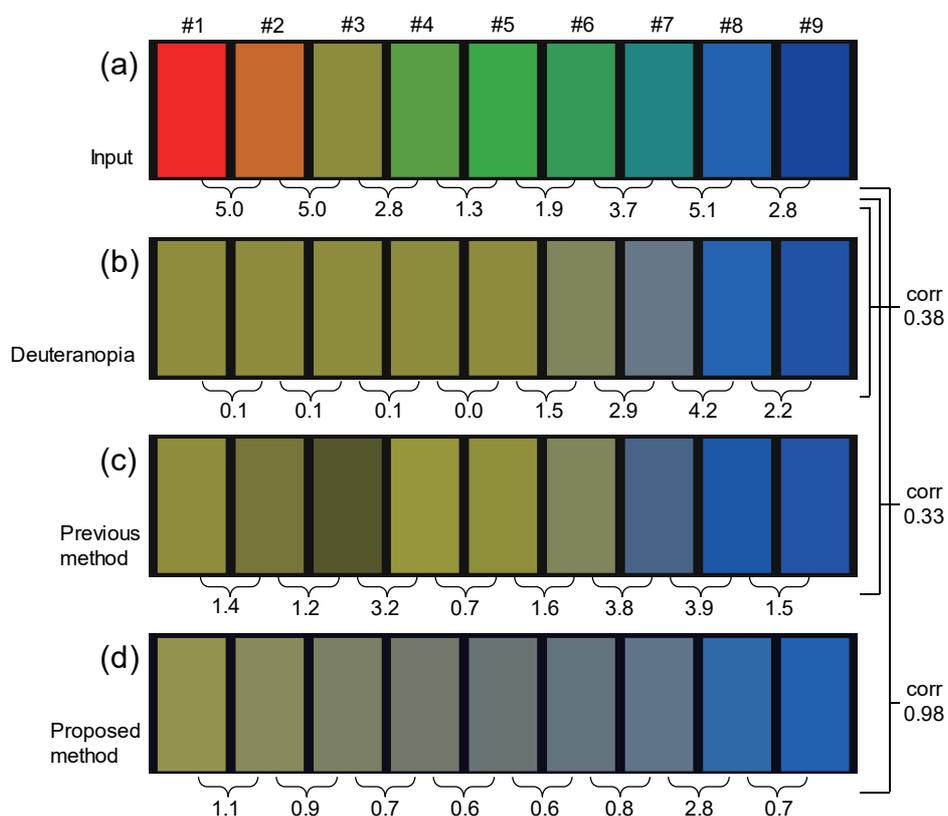
Fig. 4. Evaluation: (a) Input image observed by trichromats, (b) the image (a) perceived by deuteranopia, (c) the result of previous method, and (d) the result of our method

Table 1. Color difference between neighboring patches

Patches	Input	Dichromat	Previous	Proposed
#1&#2	4.95	0.11	1.37	1.14
#2&#3	4.97	0.09	1.18	0.91
#3&#4	2.77	0.13	3.21	0.71
#4&#5	1.25	0.04	0.72	0.61
#5&#6	1.90	1.50	1.62	0.64
#6&#7	3.67	2.90	3.78	0.76
#7&#8	5.10	4.18	3.87	2.82
#8&#9	2.83	2.16	1.54	0.75
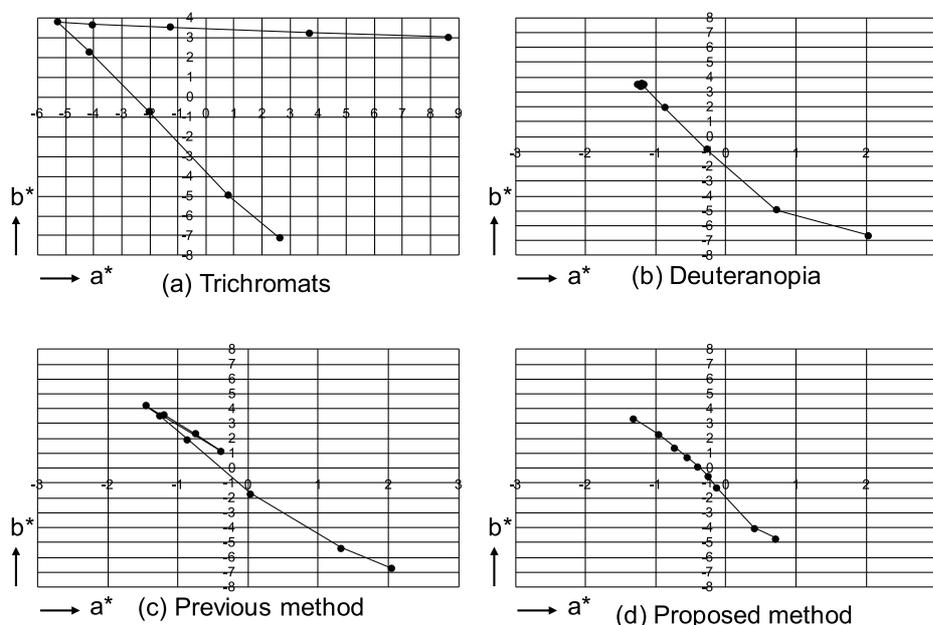
Fig. 5. The color of 9 patches plotted in a*b* space: (a) The plot of Figure 4 (a), (b) the plot of Figure 4 (b), (c) the plot of Figure 4 (c), and (d) the plot of Figure 4 (d)

protanopia, which gives the same insight.

3.2. *Qualitative evaluation*

In this section, we show some results applied to various images.

Figures 6–10 show the result of deuteranopia, and Figures 11–15 show the result of protanopia. For each image, "(a)" represents the input image, "(b)" represents the simulated image where the dichromats see the figure (a), "(c)" represents the output of Huang[8], and "(d)" represents the output of our method. The computation time is less than one second for common computers, even though we have not fine-tuned our implementation.

Figures 6, 7, 11, and 12 are the results where both methods work well. For example, Figure 12 (a) is perceived as "17" by dichromats as is shown in Figure 12 (b), while our method clearly shows "15" as is shown in Figure 12 (d).

Figures 8, 9, 13, 10, and 14 are the results where our results outperforms Huang's results. Our method expands the color variation than Huang's method as is shown in Figure 8 and Figure 13. The red pepper and the green pepper are distinguishable in Figure 9 (d), and those peppers have different color from the rack. Figure 10 is difficult to say which result is better, however, we would like to say that our background is more bluish than Huang's background, which improves to distinguish

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(a) Input   (b) Dichromat   (c) Previous   (d) Proposed
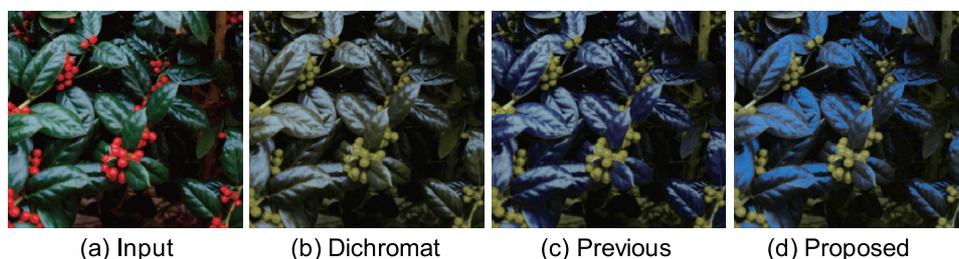
Fig. 6. Result [berry]: (a) Input image, (b) deuteranopic view, (c) previous method, and (d) our method

(a) Input   (b) Dichromat   (c) Previous   (d) Proposed
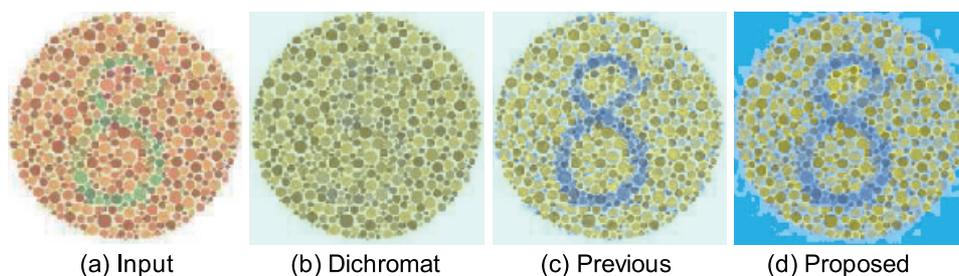
Fig. 7. Result [eight]: (a) Input image, (b) deuteranopic view, (c) previous method, and (d) our method

between the background and the flower. Although the distinguishability of patches in Figure 14 (c) is high, the color variation of Figure 14 (d) smoothly resembles Figure 14 (a), which we would like to emphasize that the advantage of our method is that the correlation of color difference between dichromats and trichromats is high.

Figure 15 (a) looks as if it is quite a simple task, however, both methods fail to improve the visibility. Since this problem is common in both methods, the cause might be the approach itself; namely, the hue histogram equalization. Our future work is to install additional process to our algorithm in order to overcome the problem caused by hue histogram equalization.

Other results are shown in Figure 16.

4. Conclusion

We have developed a method which improves the visibility of dichromats. We have defined a hue parameter for dichromats, and converted the hue of trichromats to the hue of dichromats. We have shown that the hue parameter we used has one-to-one correspondence with L*a*b* hue. We have equalized the histogram of hue so

(a) Input   (b) Dichromat   (c) Previous   (d) Proposed
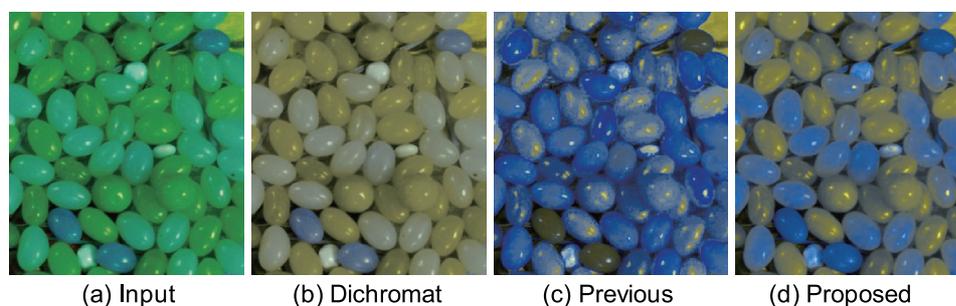
Fig. 8. Result [beans]: (a) Input image, (b) deuteranopic view, (c) previous method, and (d) our method

(a) Input   (b) Dichromat   (c) Previous   (d) Proposed
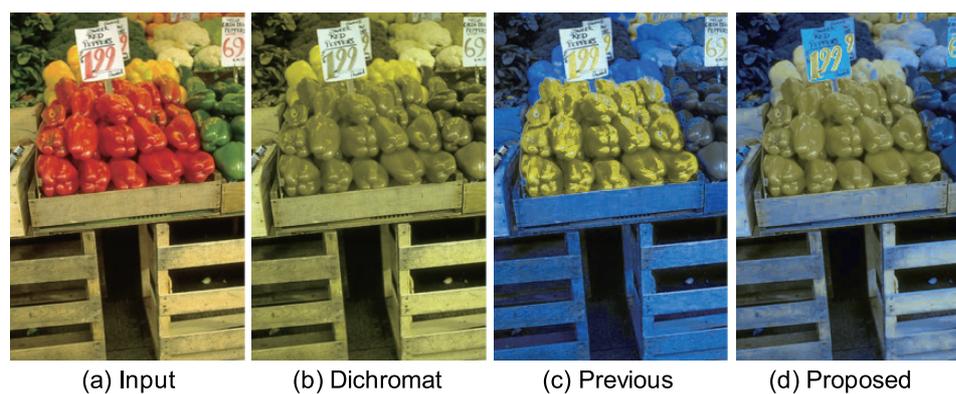
Fig. 9. Result [pepper]: (a) Input image, (b) deuteranopic view, (c) previous method, and (d) our method

(a) Input   (b) Dichromat   (c) Previous   (d) Proposed
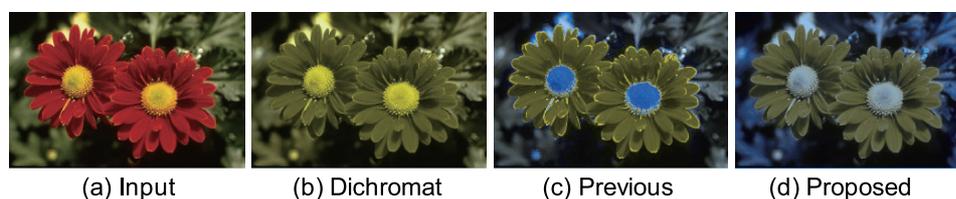
Fig. 10. Result [flower]: (a) Input image, (b) deuteranopic view, (c) previous method, and (d) our method

that the dichromats can recognize the color difference as much as possible. We have shown a numerical evaluation in order to empirically prove the high performance

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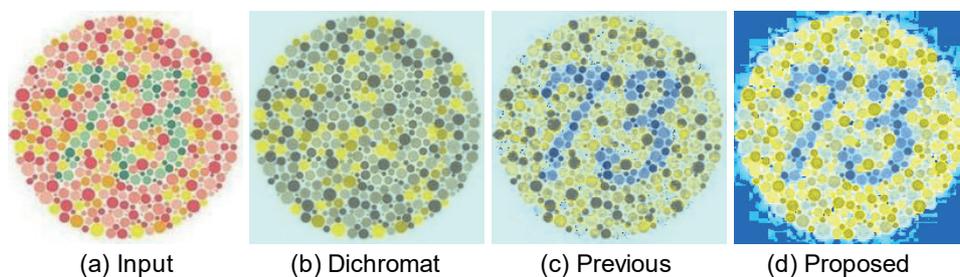
Fig. 11. Result [seventy-three]: (a) Input image, (b) protanopic view, (c) previous method, and (d) our method
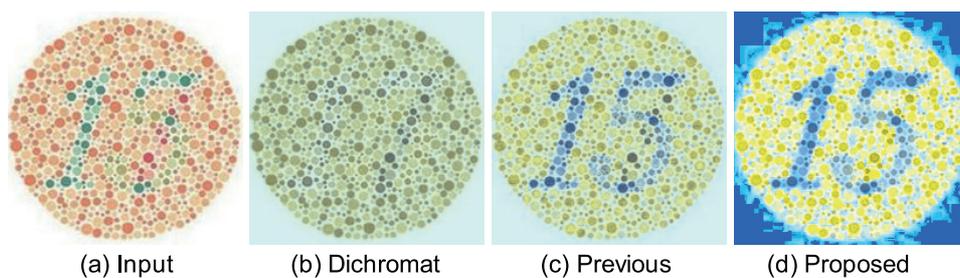
Fig. 12. Result [fifteen]: (a) Input image, (b) protanopic view, (c) previous method, and (d) our method
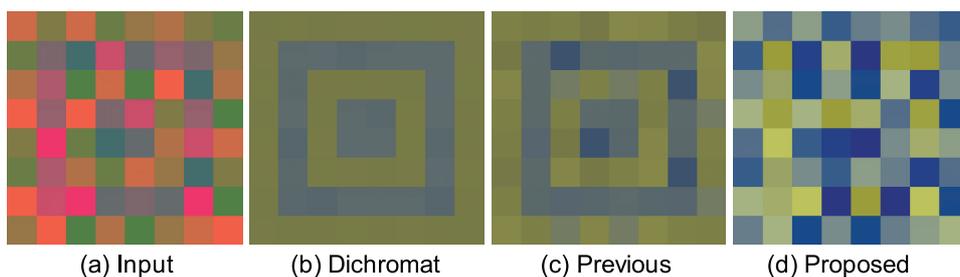
Fig. 13. Result [patches]: (a) Input image, (b) protanopic view, (c) previous method, and (d) our method

of our method. Especially, our method produces an image where the dichromats perceive the similar color difference to the trichromats.

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| (a) Input | (b) Dichromat | (c) Previous | (d) Proposed |
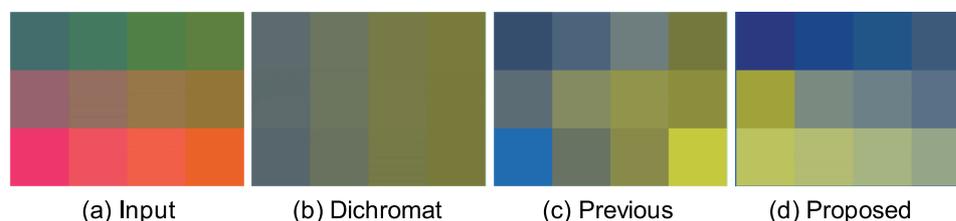
Fig. 14. Result [gradation]: (a) Input image, (b) protanopic view, (c) previous method, and (d) our method

| (a) Input | (b) Dichromat | (c) Previous | (d) Proposed |
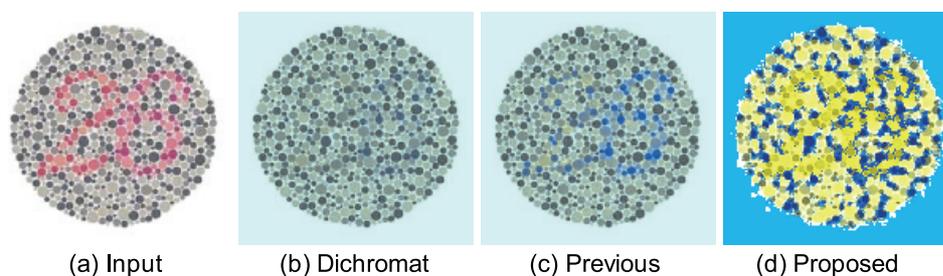
Fig. 15. Result [twenty-six]: (a) Input image, (b) protanopic view, (c) previous method, and (d) our method

Acknowledgments

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| (a) Input | (b) Dichromat | (c) Previous | (d) Proposed |
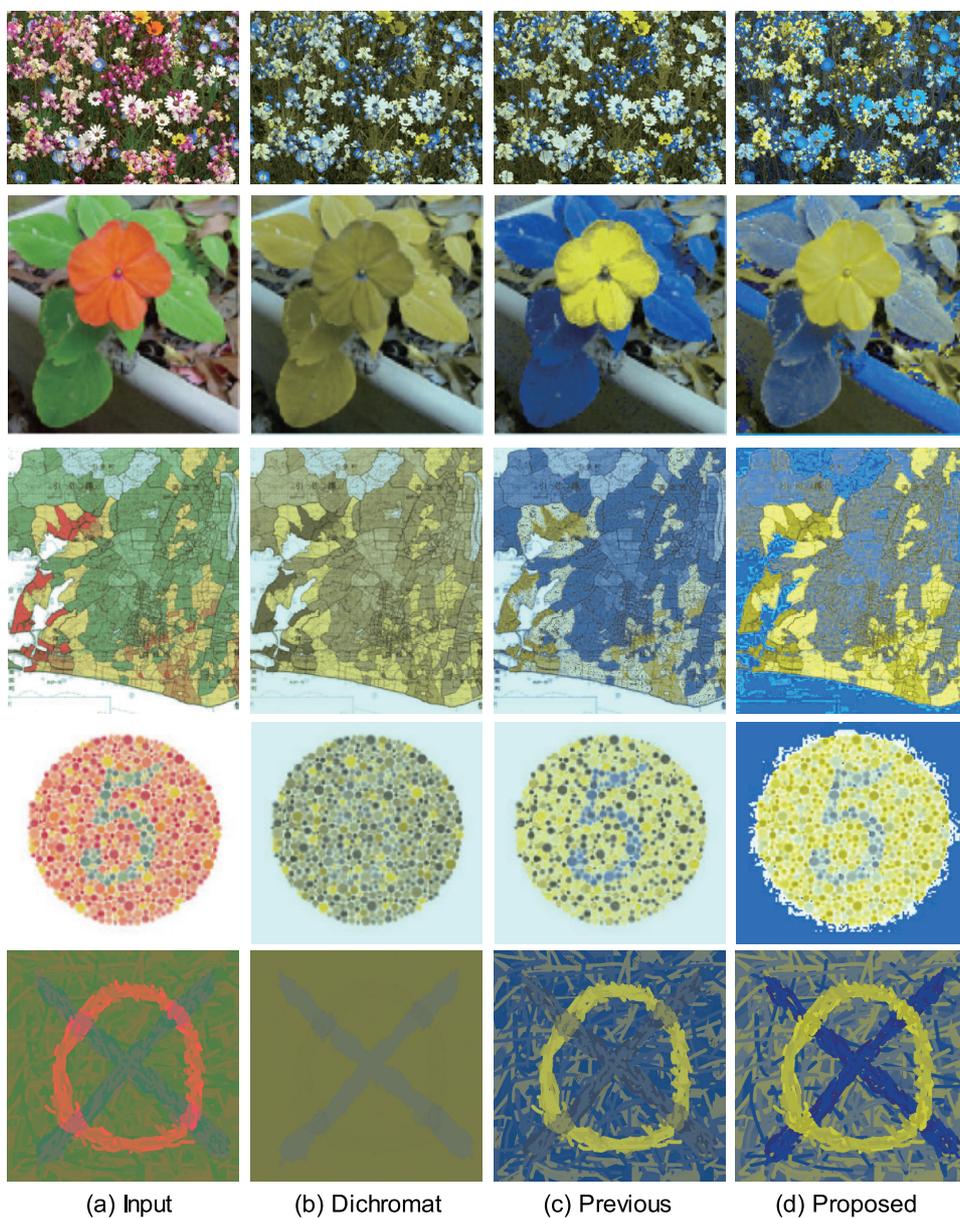
Fig. 16. Results [others]: (a) Input image, (b) protanopic view, (c) previous method, and (d) our method

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