ICIC Express Letters
Part B: Applications
Volume **12**, Number **7**, July **2021**

ICIC International ©2021 ISSN 2185-2766
pp. **611–617**

COMPUTATIONAL COST REDUCTION OF QUANTITATIVE EVALUATION INDICES OF CONTRAST IMPROVEMENT FOR DICHROMATS

Xi Cheng and Go Tanaka

Graduate School of Science
Nagoya City University
1, Yamanohata, Mizuho-cho, Mizuho-ku, Nagoya 467-8501, Japan
{ chengxi; tanakago }@nsc.nagoya-cu.ac.jp

Received November 2020; accepted February 2021

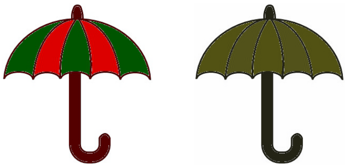
Abstract. *Although color is an important factor in visual information, people with color vision deficiency cannot discriminate specific color combinations. In recent years, many methods to improve the contrast for people by changing colors in images have been proposed. In addition, several quantitative evaluation indices to evaluate the contrast improvement degree have been proposed. However, the computational cost of the indices is large. In this Letter, we propose the computational cost reduction of two indices. Experimental results show that the proposed indices realize computational cost reduction without deteriorating their performance.*

Keywords: Dichromacy, Contrast improvement, Quantitative evaluation, Computational cost reduction

1. **Introduction.** Color is very important in daily life. However, among European Caucasians, about 8% of men and about 0.4% of women have red-green color deficiency, as well as between 4% and 6.5% of men of Chinese and Japanese ethnicity [1]. These people have difficulty in distinguishing specific colors, and some important color information cannot be sufficiently received. Figure 1 shows an example of indiscriminable colors for people with protanopia. Figure 1(b) shows how Figure 1(a) is observed by people with protanopia; these images were obtained using the model proposed by Viénot et al. [2]. It is necessary to understand the difficulties experienced by people with color deficiency and to improve their situation. In this Letter, we focus on dichromacy, which contains three types of color vision deficiency: protanopia (P-type), deuteranopia (D-type), and tritanopia (T-type). These three types are collectively referred to as K-type color vision hereafter. In addition, normal trichromacy is referred to as N-type color vision.

As mentioned above, dichromats may experience inconvenience in their daily lives. To solve this problem, many methods to improve the contrast for dichromats by changing the colors in images have been studied in recent years. The evaluation of the converted images (contrast improvement degree) is also important. Tanaka et al. [3] proposed the evaluation index V_{K} for the contrast improvement degree. V_{K} evaluates the difference between the contrast of an original image for N-type color vision and that of a color-converted image for K-type color vision. In addition, indices based on V_{K} have been proposed [4, 5, 6, 7, 8] and there is an index [9] which is essentially the same as V_{K} defined in [5]. Indices proposed in [3, 4] evaluate the contrast of all pixel pairs in images. On the other hand, the indices proposed in [5, 6, 7, 8, 9] evaluate the contrast of neighboring pixel pairs in images. The computational cost of the indices in [5, 6, 7, 8, 9] is smaller than that of indices proposed in [3, 4]. However, the cost also increases as the neighborhood range increases. Although reducing the computational cost is desirable, it has not been investigated.

DOI: 10.24507/icicelb.12.07.611



(a) (b)

FIGURE 1. Color images observed by people with (a) normal trichromacy and (b) protanopia

In this Letter, we propose the computational cost reduction of two indices of contrast improvement by the random pairing of neighboring pixels. $\check{V}_{\mathrm{K}}$ proposed in [7] and $\hat{V}_{\mathrm{K}}$ proposed in [8] are considered because these are state-of-the-art indices and have good correspondence with a subjective evaluation.

The rest of this Letter is organized as follows. The previous evaluation indices $\check{V}_{\mathrm{K}}$ and $\hat{V}_{\mathrm{K}}$, which consider pairs of neighboring pixels in images, are explained in Section 2. The proposed method is described in Section 3. In Section 4, the validity of the proposed method is confirmed through experiments. Finally, conclusions and future work are given in Section 5.

2. Previous Evaluation Indices.

2.1. Evaluation index $\check{V}_{\mathrm{K}}$.

In [7], $\check{V}_{\mathrm{K}}$ is defined as

$$\check{V}_{\mathrm{K}} = \check{U}_{\mathrm{K}}^{\mathrm{out}} / \check{U}_{\mathrm{K}}^{\mathrm{in}} \tag{1}$$

with

$$\check{U}_{\mathrm{K}}^{\mathrm{out}} = \sum_{(i,j)\in S} w'_{ij} \left| \check{\lambda}_E \Delta \check{E}_{\mathrm{K},ij}^{\mathrm{out}} - \Delta E_{\mathrm{N},ij}^{\mathrm{in}} \right| \tag{2}$$

and

$$\check{U}_{\mathrm{K}}^{\mathrm{in}} = \sum_{(i,j)\in S} w'_{ij} \left| \check{\lambda}_E \Delta \check{E}_{\mathrm{K},ij}^{\mathrm{in}} - \Delta E_{\mathrm{N},ij}^{\mathrm{in}} \right|. \tag{3}$$

$\Delta E_{\mathrm{N},ij}^{\mathrm{in}}$ is the color difference between the ith and jth pixels in an input image perceived in N-type color vision, and is defined as

$$\Delta E_{\mathrm{N},ij}^{\mathrm{in}} = \sqrt{\left(\Delta L_{\mathrm{N},ij}^{*\mathrm{in}}\right)^2 + \left(\Delta a_{\mathrm{N},ij}^{*\mathrm{in}}\right)^2 + \left(\Delta b_{\mathrm{N},ij}^{*\mathrm{in}}\right)^2}. \tag{4}$$

Here, L^*, a^*, and b^* are values in the CIE $L^*a^*b^*$ color space [10]. For example, $\Delta L_{\mathrm{N},ij}^{*\mathrm{in}}$ is defined as $L_{\mathrm{N},i}^{*\mathrm{in}} - L_{\mathrm{N},j}^{*\mathrm{in}}$. $L_{\mathrm{N},i}^{*\mathrm{in}}$ is the L^* component of the ith pixel in an input image perceived in N-type color vision. The definitions of $\Delta a_{\mathrm{N},ij}^{*\mathrm{in}}$ and $\Delta b_{\mathrm{N},ij}^{*\mathrm{in}}$ are similar to that of $\Delta L_{\mathrm{N},ij}^{*\mathrm{in}}$. $\Delta \check{E}_{\mathrm{K},ij}^{\mathrm{out}}$ in Equation (2) is an adjusted color difference between the ith and jth pixels in an output image perceived in K-type color vision, and is defined as

$$\Delta \check{E}_{\mathrm{K},ij}^{\mathrm{out}} = \sqrt{\check{\lambda}_{L^*}\left(\Delta L_{\mathrm{K},ij}^{*\mathrm{out}}\right)^2 + \left(\Delta a_{\mathrm{K},ij}^{*\mathrm{out}}\right)^2 + \left(\Delta b_{\mathrm{K},ij}^{*\mathrm{out}}\right)^2}. \tag{5}$$

$\Delta \check{E}_{\mathrm{K},ij}^{\mathrm{in}}$ in Equation (3) is defined in a similar manner to $\Delta \check{E}_{\mathrm{K},ij}^{\mathrm{out}}$. S is the set of pixel pairs (i,j) satisfying $d(i,j) \le \rho$, where $d(i,j)$ denotes the chessboard distance [10] between the ith and jth pixels, and ρ is the size of the neighborhood considered. w'_{ij} is the weight defined in [6] as

$$w'_{ij} = \exp\left[-\frac{\left(\Delta L_{\mathrm{N},ij}^{*\mathrm{in}}\right)^2}{2\lambda_{L^*}^2}\right] \exp\left[-\frac{\left(\Delta b_{\mathrm{N},ij}^{*\mathrm{in}}\right)^2}{2\lambda_{b^*}^2}\right] \left\{1 - \exp\left[-\frac{\left(\Delta a_{\mathrm{N},ij}^{*\mathrm{in}}\right)^2}{2\lambda_{a^*}^2}\right]\right\}, \tag{6}$$

where $\lambda_{L^*}, \lambda_{a^*}$, and λ_{b^*} are parameters with positive real values. When colors of the ith and jth pixels are difficult to distinguish in K-type color vision, the weight w'_{ij} becomes large. $\check{\lambda}_E$ and $\check{\lambda}_{L^*}$ in Equations (2), (3), and (5) are parameters with nonnegative real numbers.

For $\check{V}_{\mathrm{K}}$, the contrast is evaluated using the (adjusted) color difference. $\check{U}_{\mathrm{K}}^{\mathrm{out}}$ is the weighted sum of differences of contrasts perceived in K-type and N-type color vision. If the contrasts are similar, $\check{U}_{\mathrm{K}}^{\mathrm{out}}$ is close to 0 and then $\check{V}_{\mathrm{K}}$ is close to 0. $\check{U}_{\mathrm{K}}^{\mathrm{in}}$ is used for the normalization of $\check{V}_{\mathrm{K}}$ (Equation (1)) and, in general, the range of $\check{V}_{\mathrm{K}}$ is $[0, 1]$. However, the contrast of an output image is sometimes lower than that of an input image $\left(\Delta\check{E}_{\mathrm{K},ij}^{\mathrm{out}} < \Delta\check{E}_{\mathrm{K},ij}^{\mathrm{in}}\right)$ or very high $\left(\Delta\check{E}_{\mathrm{K},ij}^{\mathrm{out}} \gg \Delta E_{\mathrm{N},ij}^{\mathrm{in}}\right)$, and in these cases, $\check{V}_{\mathrm{K}}$ may be larger than 1. When the contrast of an output image is very high relative to that of an input image, $\check{U}_{\mathrm{K}}^{\mathrm{out}}$ (and $\check{V}_{\mathrm{K}}$) becomes large, indicating that the output image is unsuitable for K-type color vision (even though the contrast of the image is high). $\check{\lambda}_E$ is a parameter used to solve this problem by compressing $\Delta\check{E}_{\mathrm{K},ij}^{\mathrm{out}}$ and $\check{\lambda}_E$ should be smaller than 1. $\check{\lambda}_{L^*}$ is a parameter used to increase the importance of the lightness component, because humans are sensitive to lightness differences, and $\check{\lambda}_{L^*}$ should be larger than 1.

2.2. **Evaluation index $\hat{V}_{\mathrm{K}}$.** In [8], $\hat{V}_{\mathrm{K}}$ is defined as

$$\hat{V}_{\mathrm{K}} = \hat{U}_{\mathrm{K}}^{\mathrm{out}} / \hat{U}_{\mathrm{K}}^{\mathrm{in}} \tag{7}$$

with

$$\hat{U}_{\mathrm{K}}^{\mathrm{out}} = \frac{1}{|S_{\mathrm{K}}|} \sum_{(i,j)\in S_{\mathrm{K}}} \left| \hat{\lambda}_E \Delta\hat{E}_{\mathrm{K},ij}^{\mathrm{out}} - \Delta E_{\mathrm{N},ij}^{\mathrm{in}} \right| \tag{8}$$

and

$$\hat{U}_{\mathrm{K}}^{\mathrm{in}} = \frac{1}{|S_{\mathrm{K}}|} \sum_{(i,j)\in S_{\mathrm{K}}} \left| \hat{\lambda}_E \Delta\hat{E}_{\mathrm{K},ij}^{\mathrm{in}} - \Delta E_{\mathrm{N},ij}^{\mathrm{in}} \right|. \tag{9}$$

Here, $\Delta\hat{E}_{\mathrm{K},ij}^{\mathrm{out}}$ is an adjusted color difference defined as

$$\Delta\hat{E}_{\mathrm{K},ij}^{\mathrm{out}} = \sqrt{\hat{\lambda}_{L^*} \left(\Delta L_{\mathrm{K},ij}^{*\mathrm{out}}\right)^2 + \left(\Delta a_{\mathrm{K},ij}^{*\mathrm{out}}\right)^2 + \left(\Delta b_{\mathrm{K},ij}^{*\mathrm{out}}\right)^2}. \tag{10}$$

$\Delta\hat{E}_{\mathrm{K},ij}^{\mathrm{in}}$ is also defined in a similar manner to $\Delta\hat{E}_{\mathrm{K},ij}^{\mathrm{out}}$. In Equations (8) and (9), S_{K} is the set of pixel pairs (i, j) satisfying $d(i, j) \leq \rho$ and $T_{\mathrm{K},ij} \leq \tau$ simultaneously. $T_{\mathrm{K},ij}$ is defined as

$$T_{\mathrm{K},ij} = \Delta E_{\mathrm{K},ij}^{\mathrm{in}} / \Delta E_{\mathrm{N},ij}^{\mathrm{in}}. \tag{11}$$

Here, $\Delta E_{\mathrm{K},ij}^{\mathrm{in}}$ is defined as

$$\Delta E_{\mathrm{K},ij}^{\mathrm{in}} = \sqrt{\left(\Delta L_{\mathrm{K},ij}^{*\mathrm{in}}\right)^2 + \left(\Delta a_{\mathrm{K},ij}^{*\mathrm{in}}\right)^2 + \left(\Delta b_{\mathrm{K},ij}^{*\mathrm{in}}\right)^2}. \tag{12}$$

τ is a parameter with a nonnegative real number. $|S_{\mathrm{K}}|$ is the number of elements in S_{K}.

$T_{\mathrm{K},ij}$ is the ratio between the contrasts of the colors of the ith and jth pixels of an input image for K-type and N-type color vision. When $T_{\mathrm{K},ij} \ll 1$, the colors of the ith and jth pixels are indiscriminable in K-type color vision. Therefore, when τ is small, S_{K} is the set of pixel pairs with indiscriminable colors. $\check{\lambda}_E$ and $\check{\lambda}_{L^*}$ have the same meaning as $\hat{\lambda}_E$ and $\hat{\lambda}_{L^*}$, respectively. Similarly to $\check{V}_{\mathrm{K}}$, the range of $\hat{V}_{\mathrm{K}}$ is generally $[0, 1]$.

3. **Proposed Method.** In this section, we propose the computational cost reduction of $\check{V}_{\mathrm{K}}$ and $\hat{V}_{\mathrm{K}}$ by random pairing. The new indices are represented by $\check{V}'_{\mathrm{K}}$ and $\hat{V}'_{\mathrm{K}}$, respectively. The definition of $\check{V}'_{\mathrm{K}}$ is identical to that of $\check{V}_{\mathrm{K}}$ except for the definition of S. Similarly, the definition of $\hat{V}'_{\mathrm{K}}$ is identical to that of $\hat{V}_{\mathrm{K}}$ except for the definition of S_{K}. For $\check{V}'_{\mathrm{K}}$ and $\hat{V}'_{\mathrm{K}}$,

S and S_{K} are respectively replaced by S' and S'_{K}. These new pixel pair sets are defined below.

First, the set S_i is defined. The elements of S_i are the pixels j satisfying $d(i,j) \leq \rho$. In addition, the random choosing operator 'rand' is defined. It randomly chooses one element from a target set. The elements of S' are pixel pairs (i, j_i), where $j_i = \mathrm{rand}(S_i)$. The elements of S'_{K} are pixel pairs (i,j) satisfying $(i,j) \in S'$ and $T_{\mathrm{K},ij} \leq \tau$ simultaneously. S' and S'_{K} are subsets of S and S_{K}, respectively.

The number $|S|$ of elements in S can be approximately[1] expressed as

$$|S| \approx (2\rho + 1)^2 \times W \times H, \tag{13}$$

where W and H are the width and height of an image, respectively. The number $|S'|$ of elements in S' is

$$|S'| = W \times H. \tag{14}$$

$|S'|$ is about $(2\rho+1)^2$ times smaller than $|S|$. $|S_{\mathrm{K}}|$ and $|S'_{\mathrm{K}}|$ depend on not only ρ but also the contents of an input image because the condition $T_{\mathrm{K},ij} \leq \tau$ is imposed. Therefore, they cannot be generally formulated.

4. **Experiment.** It can be theoretically understood that the computational cost of the proposed indices is smaller than that of the previous indices as shown in Equations (13) and (14). In Section 4.1, the actual calculation time is discussed. In addition, $\check{V}'$ and $\hat{V}'$ should have a satisfactory evaluation ability compared with $\check{V}$ and $\hat{V}$, respectively, which is verified in Section 4.2.

In this Letter, we show results for P-type color vision. That is, we employ $\check{V}_{\mathrm{P}}$, $\hat{V}_{\mathrm{P}}$, $\check{V}'_{\mathrm{P}}$, and $\hat{V}'_{\mathrm{P}}$ in experiments. The color appearance in P-type color vision is simulated using the model proposed by Viénot et al. [2]. The images shown in Figure 2 are used in experiments. The size of each image is 281×276 pixels. The hue of each image is changed in the HSL color space [11] at 15° intervals and 24 conversion results[2] are obtained as shown in Figure 3.

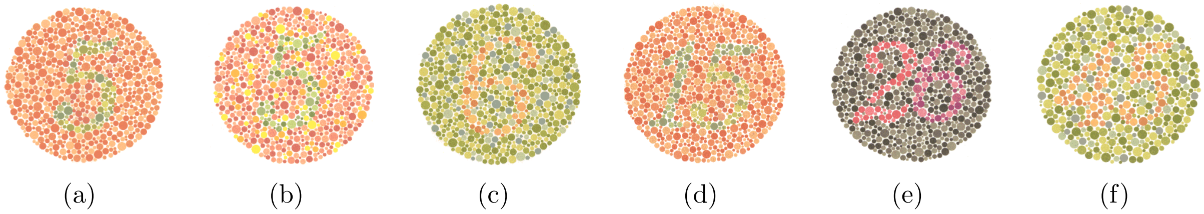


Figure 2. Experimental images: (a) Chart 5a, (b) Chart 5b, (c) Chart 6, (d) Chart 15, (e) Chart 26, and (f) Chart 45

ρ, which is the common parameter of $\check{V}_{\mathrm{P}}$ and $\hat{V}_{\mathrm{P}}$, is set as 5, 10, 15, and 20. The other parameters of $\check{V}_{\mathrm{P}}$ are set as $\left(\lambda_{L^*}, \lambda_{a^*}, \lambda_{b^*}, \check{\lambda}_E, \check{\lambda}_{L^*}\right) = (2, 15, 7, 0.4, 9)$ and those of $\hat{V}_{\mathrm{P}}$ are set as $\left(\tau, \hat{\lambda}_E, \hat{\lambda}_{L^*}\right) = (0.4, 0.3, 10)$. The parameters of $\check{V}'_{\mathrm{P}}$ and $\hat{V}'_{\mathrm{P}}$ are set to have the same values as those of $\check{V}_{\mathrm{P}}$ and $\hat{V}_{\mathrm{P}}$, respectively.

4.1. **Calculation time.** The experimental environment is outlined in Table 1. The calculation time of each index is shown in Table 2. Here, the calculation time for the 24 hue conversion results of Chart 5b (Figure 3) is measured. The calculation time of $\check{V}_{\mathrm{P}}$ is

---

[1] When pixel i of interest is at the edge of an image, the number of pixels j satisfying $d(i,j) \leq \rho$ is less than $(2\rho + 1)^2$.

[2] Hue conversion results include the case where the amount of hue change is 0°. In this case, the output image is identical to the original image.

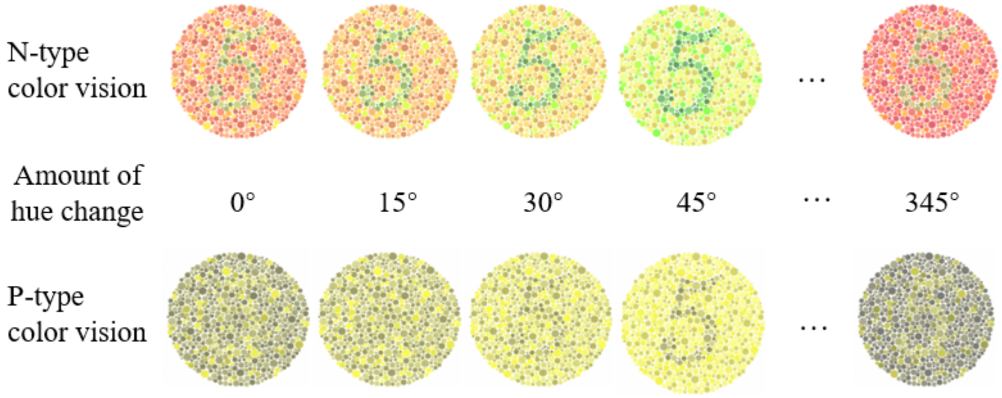


Figure 3. Example of hue conversion

Table 1. Experimental environment

CPU	Intel® Core™ i7-8700 (3.2 GHz)
Main memory	8 GB
Operating system	Windows 10 Pro 64bit
Program language	C

Table 2. Calculation time for 24 hue conversion results of Chart 5b (Figure 3) with different ρ values. The unit is second.

ρ	5	10	15	20
$\check{V}_{\text{P}}$	26.9	93.3	201.7	354.9
$\check{V}'_{\text{P}}$	2.3	2.3	2.3	2.3
$\hat{V}_{\text{P}}$	15.5	50.7	113.3	190.8
$\hat{V}'_{\text{P}}$	2.3	2.3	2.3	2.3

proportional to ρ^2 and corresponds to $|S|$ (Equation (13)). On the other hand, the calculation time of $\check{V}'_{\text{P}}$ is constant and corresponds to $|S'|$ (Equation (14)). The calculation times of $\hat{V}_{\text{P}}$ and $\hat{V}'_{\text{P}}$ are also proportional to ρ^2 and constant, respectively.

Although $|S|/|S'| \approx (2\rho + 1)^2$ from Equations (13) and (14), the ratio of the actual calculation times of $\check{V}$ and $\check{V}'$ differs from this value. The calculation time shown in Table 2 includes the processing time of the image reading and color space conversion (RGB to $L^*a^*b^*$). These are common processes in V and V', and they take 2.0 s. When $\rho = 5$, the ratio of the actual calculation times of $\check{V}_{\text{P}}$ and $\check{V}'_{\text{P}}$ excluding the common processes is $(26.9 - 2.0)/(2.3 - 2.0) = 83$, i.e., significantly less than 121 $(= (2 \times 5 + 1)^2)$. This is because the processing time of random value generation is required in the calculation of $\check{V}'_{\text{P}}$.

4.2. **Verification of evaluation ability.** It is desirable that evaluation indices have good correspondence with a subjective evaluation result, and from this viewpoint, it is experimentally shown that $\rho = 10$ is reasonable (see Appendix). Figures 4(a) and 4(b) show the relationship between the amount of hue change and the evaluation value for Chart 5b when $\rho = 10$. In the figures, the error ratio (ER), which is computed as $\left|\hat{V}_{\text{P}} - \hat{V}'_{\text{P}}\right| \Big/ \hat{V}_{\text{P}}$ or $\left|\check{V}_{\text{P}} - \check{V}'_{\text{P}}\right| / \check{V}_{\text{P}}$, is also shown. As shown in the figures, the evaluation values (graph shape) of V and V' are almost the same. That is, $\check{V}'$ and $\hat{V}'$ respectively have equivalent performance to $\check{V}$ and $\hat{V}$.

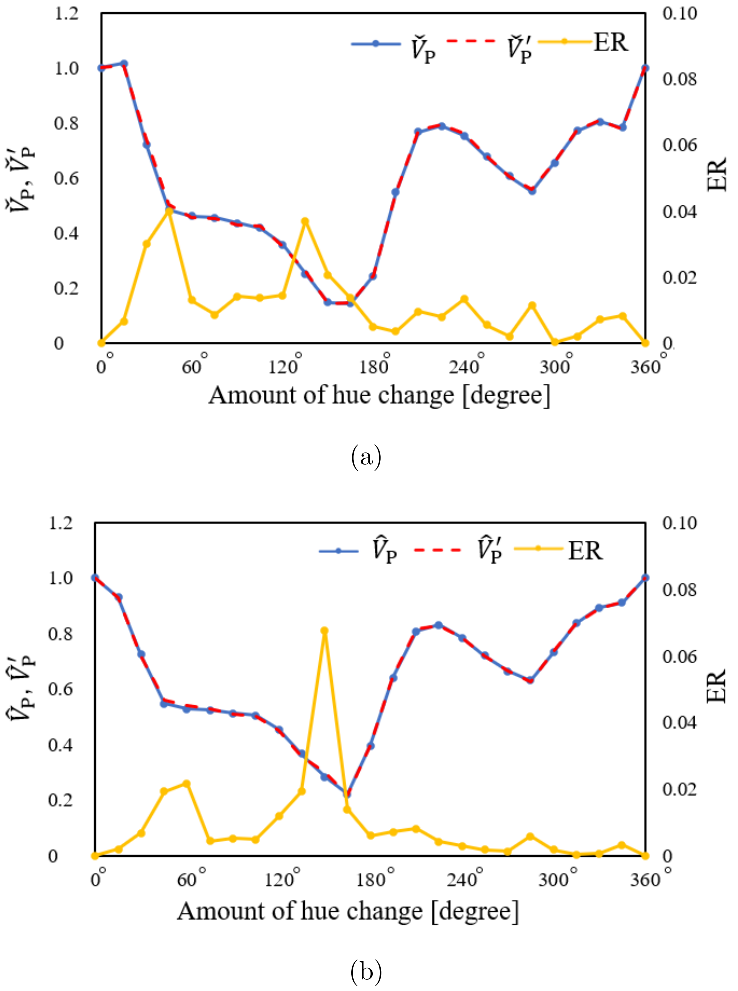


FIGURE 4. Evaluation values for Chart 5b ($\rho = 10$): (a) $\check{V}_\mathrm{P}$ and $\check{V}'_\mathrm{P}$, and (b) $\hat{V}_\mathrm{P}$ and $\hat{V}'_\mathrm{P}$

5. **Conclusions.** In this Letter, we examined evaluation indices of contrast improvement for dichromacy that select pixel pairs by random pairing. Through experiments, the proposed indices were confirmed to have equivalent evaluation performance to the previous indices while reducing the computational cost. Constructing a contrast improvement method for dichromats using the evaluation indices proposed in this Letter is future work.

REFERENCES

[1] J. Birch, Worldwide prevalence of red-green color deficiency, *Journal of the Optical Society of America A*, vol.29, no.3, pp.313-320, 2012.

[2] F. Viénot, H. Brettel and J. D. Mollon, Digital video colourmaps for checking the legibility of displays by dichromats, *Color Research and Application*, vol.24, no.4, pp.243-252, 1999.

[3] G. Tanaka, N. Suetake and E. Uchino, Lightness modification of color image for protanopia and deuteranopia, *Optical Review*, vol.17, no.1, pp.14-23, 2010.

[4] H. Takimono, H. Yamauchi, M. Jindai and A. Kanagawa, Modification of indistinguishable colors for people with color vision deficiency, *Journal of Signal Processing*, vol.16, no.6, pp.587-592, 2012.

[5] M. Meng and G. Tanaka, Proposal of minimization problem based lightness modification for protanopia and deuteranopia, *Proc. of 2016 International Symposium on Intelligent Signal Processing and Communication Systems*, Phuket, Thailand, pp.215-220, 2016.

[6] M. Meng and G. Tanaka, Proposal of minimization problem based lightness modification method considering visual characteristics of protanopia and deuteranopia, *Proc. of Asia-Pacific Signal and Information Processing Association Annual Summit and Conference 2019*, Lanzhou, China, pp.1417-1422, 2019.

[7] X. Cheng and G. Tanaka, Quantitative evaluation method of contrast improvement for protanopia and deuteranopia, *Proc. of 2020 IEICE General Conference*, no.A-15-10, p.132, 2020 (in Japanese).

[8] X. Cheng and G. Tanaka, A novel quantitative evaluation index of contrast improvement for dichromats, *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, vol.E103-A, no.12, pp.1618-1620, 2020.

[9] G. M. Machado and M. M. Oliveira, Real-time temporal-coherent color contrast enhancement for dichromats, *Computer Graphics Forum*, vol.29, no.3, pp.933-942, 2010.

[10] R. C. Gonzalez and R. E. Woods, *Digital Image Processing*, 3rd Edition, Prentice Hall, New Jersey, 2008.

[11] M. K. Agoston, *Computer Graphics and Geometric Modeling: Implementation and Algorithms*, Springer-Verlag, London, 2005.

[12] L. L. Thurstone, A law of comparative judgment, *Psychological Review*, vol.34, no.4, pp.273-286, 1927.

Appendix: Reasonable Value of ρ. In this Letter, the subjective evaluation result was obtained by Thurstone's paired comparison method[3] [12] and expressed by $\bar{R}$. Note that small V means a good result but small $\bar{R}$ means a poor result. In addition, the ranges of V and $\bar{R}$ are different. To compare indices V and $\bar{R}$, the adjustment described in [8] is required.

In the experiment in this Letter, 24 hue conversion results are obtained for each image. The mean square error (MSE) between the adjusted V and $\bar{R}$ for an image is computed from the evaluation values for the 24 conversion results. Average MSE values for six experimental images are shown in Table 3. The table shows that $\rho = 10$ is appropriate for $\check{V}'_{\mathrm{P}}$, $\hat{V}_{\mathrm{P}}$, and $\hat{V}'_{\mathrm{P}}$, and $\rho = 20$ is appropriate for $\check{V}_{\mathrm{P}}$ in this experiment: ρ is set to 5, 10, 15, or 20. Although the difference in average MSE for $\check{V}_{\mathrm{P}}$ when $\rho = 10$ and $\rho = 20$ is small (0.0007), the difference in computational cost is large. Therefore, it is concluded that $\rho = 10$ is reasonable for $\check{V}_{\mathrm{P}}$.

Table 3. Average MSE between each adjusted V and $\bar{R}$ for six experimental images

ρ	5	10	15	20
$\check{V}_{\mathrm{P}}$	0.0797	0.0707	0.0705	**0.0700**
$\check{V}'_{\mathrm{P}}$	0.0818	**0.0683**	0.0702	0.0705
$\hat{V}_{\mathrm{P}}$	0.0948	**0.0905**	0.0925	0.0944
$\hat{V}'_{\mathrm{P}}$	0.0957	**0.0897**	0.0930	0.0946

---

[3] The subjects were six males and four females with N-type color vision confirmed by the Ishihara test. In the subjective evaluation experiment, an original image and two images for evaluation were presented on a screen [8]. The subjects selected the image with the higher contrast from the images for evaluation. The number of image pairs for evaluation was ${}_{24}C_2 = 276$ for each experimental image. Experiments were conducted with approval (approval number: 2019-NCU-NS-54) from the Ethical Review Committee, Graduate School of Natural Sciences (currently known as Graduate School of Science), Nagoya City University, and with the informed consent of all participating subjects.