Color Adaptation for Anomalous Trichromats

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ABSTRACT: In this article, we propose a content-based color adaptation method for color vision impairment, especially for anomalous trichromats, to improve color information accessibility. Color degradation caused by anomalous trichromacy is compensated in digital color content with a range of the visible spectrum corresponding to color deficiency characteristics. To verify the usefulness of the proposed method, we performed clinical experiments as well as computer simulations. The results of both the experiments and the simulations show that the proposed adaptation could convey better color information to anomalous trichromats. © 2004 Wiley Periodicals, Inc. Int J Imaging Syst Technol, 14, 16–20, 2004; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/ima.20002

Key words: color adaptation; anomalous trichromat; color vision deficiency; visual impairment

I. INTRODUCTION

Color is a fundamental visual feature that gives richness to the natural world. Color is more likely to be for decoration, but it is frequently used as the primary means to deliver visual information to people. In daily life, one can easily access multimedia contents with high-quality color, even in personal communication devices such as cellular phones and PDAs. As the use of color to convey visual information in the multimedia content increases, it becomes more crucial to perceive the color precisely.

Obviously color works well for people with normal color vision, but it is not effective for people with color vision deficiency (CVD). CVD is usually congenital and is inherited from parents. Worldwide, around 1 in 12 males and 1 in 200 females have CVD (McIntyre, 2002). CVD is a life-long condition; there is no complete medical treatment. However, many images, videos, and documents, including web pages containing color, are becoming popular on digital TV, in multimedia communication, and on the Internet, with no significant consideration for the above problems. The use of rich color, therefore, causes people with CVD to confuse or even misread the meaning of the information that the color carries. The problem becomes worse when the color is the only visual cue for distinguishing something.

In previous work to aid or enhance color accessibility for people with CVD, the ChromaGen system was used, which employs different colored filters in the eye to create a controlled color contrast (Swarbrick et al., 2001). The major problem with the lens, however, was that the lens also filtered out the colors that people with CVD could normally see.

In another method, color content designers avoided the colors that were confused by people with CVD. The designers could identify the confusing colors by a color simulation (Brettel et al., 1997; Walraven and Alferdinck, 1997; Rigden, 1999; Vienot and Brettel, 1999; Brettel and Vienot, 2001) or they could follow relevant guidelines on web accessibility ("Web Contents Accessibility Guidelines," 1999; "Techniques for Web Content Accessibility," 2000; "Resource Guide," 2003). But this method could only support a limited range of colors. Moreover, the use of a limited number of colors could affect the creativity of the color designer.

In this article, we propose a color adaptation method based on digital color contents to enhance color readability of anomalous trichromats. In the proposed method, color adaptation is performed according to both characteristics of defective color vision and digital display device. The CVD characteristics described in 'Visual Impairment' in MPEG-21 DIA (digital item adaptation) are used ([MPEG Requirement Group, 2002; MPEG MDS Group, 2002; Ro et al., 2002a, 2002b).

This article is composed of four sections. In Section II, we briefly describe the causes and symptoms of anomalous trichromacy. We also propose digital color adaptation for anomalous trichromats. Section III includes clinical experiments and their analysis. We conclude the article in Section IV.

II. THEORY

A. Color Perception in Anomalous Trichromats. Human color vision is generally based on the response of three photoreceptors contained in the retina of the eye. It is initiated by the absorption of photons in three classes of cones where the peak sensitivities lie in the long-wavelength (L), middle-wavelength (M), and short-wavelength (S) regions of the spectrum (McIntyre, 2002; Kaiser and Boynton, 1996). The human eye perceives a completely different color based on the sensitivity of the photoreceptors in the retina. The color being perceived through the display device is affected by the spectral emission sensitivity of the display device as well as the LMS cones' sensitivity in the eye.

The spectral responses of the L, M, and S cones can be represented by the individual primary phosphor emissions (R, G, and B phosphors) in the display. First, the spectral responses of L cone with respect to the R, G, and B phosphors can be written as

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$$L_R = \int k_l E_R(\lambda) L(\lambda)\, d\lambda,\ L_G = \int k_l E_G(\lambda) L(\lambda) d\lambda, \text{ and}$$

$$L_B = \int k_l E_B(\lambda) L(\lambda)\, d\lambda\,. \quad (1)$$

Second, the spectral responses of the M cone with respect to R, G, and B phosphors are

$$M_R = \int k_m E_R(\lambda) M(\lambda)\, d\lambda,\ M_G = \int k_m E_G(\lambda) M(\lambda)\, d\lambda, \text{ and}$$

$$M_B = \int k_m E_B(\lambda) M(\lambda)\, d\lambda\,. \quad (2)$$

Third, the spectral responses of the S cone with respect to the R, G, and B phosphors are

$$S_R = \int k_s E_R(\lambda) S(\lambda)\, d\lambda,\ S_G = \int k_s E_G(\lambda) S(\lambda)\, d\lambda, \text{ and}$$

$$S_B = \int k_s E_B(\lambda) S(\lambda)\, d\lambda\,. \quad (3)$$

In Eqs. (1)–(3), $E_R(\lambda)$, $E_G(\lambda)$, and $E_B(\lambda)$ are the primary emission functions of the R, G, and B phosphors, respectively, and $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$ are the cone's fundamental response functions over the wavelength of visible light. In this article, the display device is assumed to have an ideal emission function so that the neutral point of the LMS response is purely white. Therefore, the parameters of k in Eqs. (1)–(3) are computed with the condition to satisfy $\Sigma L = \Sigma M = \Sigma S = 1$ (Kovacs et al., 2001). Then the relationship between LMS cone responses and RGB colors can be described as

$$\begin{bmatrix} L^{normal} \\ M^{normal} \\ S^{normal} \end{bmatrix} = \mathrm{T}^{\mathrm{normal}} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} L_R^{normal} & L_G^{normal} & L_B^{normal} \\ M_R^{normal} & M_G^{normal} & M_B^{normal} \\ S_R^{normal} & S_G^{normal} & S_B^{normal} \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \quad (4)$$

where $\mathrm{T}^{\mathrm{normal}}$ is a matrix describing the relationship between the LMS cone responses and RGB colors for a normal person.

Generally, color vision deficiency is caused by the modification of one of the three cone pigments or by the complete lack of one cone (McIntyre, 2002). The former is called anomalous trichromacy and the latter is called dichromacy. Total color blindness is called achromatopsia, which means there are no cones. Anomalous trichromats make up the largest group of CVD people, more than 80% of those with CVD.

According to research in molecular genetics, the common cause of anomalous trichromacy is believed to be a shift in the peak sensitivity of a cone (Pokorny and Smith, 1977; Pokorny et al., 1977; Nathans et al., 1998; Neitz and Neitz, 2000; McIntyre, 2002). Anomalous trichromats can be divided into three types according to the shifted cone, e.g., protanomaly caused by shifted L cone, deuteranomaly caused by shifted M cone, and tritanomaly caused by shifted S cone. In anomalous trichromats, the peak sensitive wavelengths of two classes are closer than the normal trichromats in three classes of cone pigments. This causes different color sensitivities and thereby colors are confused. Also the visible color range is reduced, because of the closer two sensitivity peaks.

Therefore, in protanomaly, the L spectral response for the individual primary phosphor is defected as

$$L_R^{abnormal}(s) = k_L \int E_R(\lambda) L(\lambda - \Delta d(s))\, d\lambda,$$

$$L_G^{abnormal}(s) = k_L \int E_G(\lambda) L(\lambda - \Delta d(s))\, d\lambda,$$

$$\text{and } L_B^{abnormal}(s) = k_L \int E_B(\lambda) L(\lambda - \Delta d(s))\, d\lambda\,, \quad (5)$$

where s is the severity of anomalous trichromacy, λ is the wavelength, and $\Delta d(s)$ is the shifted amount of the abnormal cone peak sensitivity about the severity of s.

With the defected spectral responses of L cone, the LMS cone responses of a protanomaly can be written as

$$\begin{bmatrix} L^{abnormal}(s) \\ M^{normal} \\ S^{normal} \end{bmatrix} = \mathrm{T}_{\mathrm{L}}^{\mathrm{abnormal}}(s) \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} L_R^{abnormal}(s) & L_G^{abnormal}(s) & L_B^{abnormal}(s) \\ M_R^{normal} & M_G^{normal} & M_B^{normal} \\ S_R^{normal} & S_G^{normal} & S_B^{normal} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \quad (6)$$

where $\mathrm{T}_{\mathrm{M}}^{\mathrm{abnormal}}(s)$ shows the relationship function between RGB colors in display and the LMS cones' response with respect to CVD severity of s. Note that only the L response is degraded for the protanomaly and can be represented as a function of s.

Similarly, the defected color perceptions of deuteranomaly and tritanomaly could be caused by shifted M and S cones, respectively. Therefore, similar to protanomaly, $\mathrm{T}_{\mathrm{M}}^{\mathrm{abnormal}}$ for deuteranomaly and $\mathrm{T}_{\mathrm{S}}^{\mathrm{abnormal}}$ for tritanomaly can be also obtained as

$$\begin{bmatrix} L^{normal} \\ M^{abnormal}(s) \\ S^{normal} \end{bmatrix} = \mathrm{T}_{\mathrm{M}}^{\mathrm{abnormal}}(s) \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} L_R^{normal} & L_G^{normal} & L_B^{normal} \\ M_R^{abnormal}(s) & M_G^{abnormal}(s) & M_B^{abnormal}(s) \\ S_B^{normal} & S_G^{normal} & S_B^{normal} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \quad (7)$$

$$\begin{bmatrix} L^{normal} \\ M^{normal} \\ S^{abnormal}(s) \end{bmatrix} = \mathrm{T}_{\mathrm{S}}^{\mathrm{abnormal}}(s) \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} L_R^{normal} & L_G^{normal} & L_B^{normal} \\ M_R^{normal} & M_G^{normal} & M_B^{normal} \\ S_R^{abnormal}(s) & S_G^{abnormal}(s) & S_B^{abnormal}(s) \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}, \quad (8)$$

where $\mathrm{T}_{\mathrm{M}}^{\mathrm{abnormal}}(s)$ and $\mathrm{T}_{\mathrm{S}}^{\mathrm{abnormal}}(s)$ show the relationship between RGB phosphors' emission in the display and the M and S cones' responses with respective to the severity of s, respectively.

Table I. Color deficiency description in MPEG-21

	Color Vision Deficiency		
		Deficiency Degree	
Medical Terms	Deficiency Type	Textual Degree	Numerical Degree
Protanomaly	Red-Deficiency	Mild	0.1–0.9
Protanopy	Red-Deficiency	Severe	1.0
Deuteranomaly	Green-Deficiency	Mild	0.1–0.9
Deuteranopy	Green-Deficiency	Severe	1.0
Tritanomaly	Blue-Deficiency	Mild	0.1–0.9
Tritanopy	Blue-Deficiency	Severe	1.0
Achromatopsia	Complete Color Blindness	N/A	N/A

B. Characteristics of Color Vision Deficiency. As multimedia technology becomes more widely used, it is essential to have a multimedia framework to enable a transparent and augmented use of multimedia resources across different communities as well as a wide range of networks and devices (MPEG Requirement Group, 2002). That is, everyone should be able to access all kinds of digital item (or multimedia) easily and equally. For example, in accessing digital visual media, visual accessibility depends on the user's visual characteristics. If people with CVD have different CVD characteristics, they have different visual accessibility even with the same color contents.

The purpose of the MPEG-21 DIA standardization effort (MPEG MDS Group, 2002) is to provide the best experience of content consumption to the users by the adaptation of the digital multimedia contents. To improve visual accessibility, MPEG-21 DIA includes a description of the characteristics of CVD (MPEG MDS Group, 2002; Ro et al., 2002a).

In this article, the description of CVD characteristics in MPEG-21 DIA is adopted. To represent CVD, we employed the NumericalDegree type from the DIA description for CVD in MPEG-21 (MPEG Requirement Group, 2002; MPEG MDS Group, 2002; Ro et al., 2002a). Table 1 shows the medical terminology, deficiency types, and deficiency degrees of CVD in MPEG-21 (MPEG MDS Group, 2002; Ro et al., 2002a, 2002b). The NumericalDegree for the anomalous trichromat in the description is from 0.1 to 0.9, which represents the severity of s in Eqs. (6)–(8).

C. Color Adaptation for Anomalous Trichromat. As mentioned above, the characteristics of CVD and display are needed as parameters for the color adaptation. In case of protanomaly, a pixel color (R, G, B) in RGB space is defected as

$$\begin{bmatrix} R_L^{defected}(s) \\ G_L^{defected}(s) \\ B_L^{defected}(s) \end{bmatrix} = [\mathrm{T}^{\mathrm{normal}}]^{-1} \cdot \begin{bmatrix} L^{abnormal}(s) \\ M^{normal} \\ S^{normal} \end{bmatrix}, \tag{9}$$

where $[L^{abnormal}(s), M^{normal}, S^{normal}]^T$ is obtained from Eq. (6). So Eq. (9) can be rewritten as

$$\begin{bmatrix} R_L^{defected}(s) \\ G_L^{defected}(s) \\ B_L^{defected}(s) \end{bmatrix} = \begin{bmatrix} L_R^{normal} & L_G^{normal} & L_B^{normal} \\ M_R^{normal} & M_G^{normal} & M_B^{normal} \\ S_R^{normal} & S_G^{normal} & S_B^{normal} \end{bmatrix}^{-1} \cdot \begin{bmatrix} L_R^{abnormal}(s) & L_G^{abnormal}(s) & L_B^{abnormal}(s) \\ M_R^{normal} & M_G^{normal} & M_B^{normal} \\ S_R^{normal} & S_G^{normal} & S_B^{normal} \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{10}$$

In Eqs. (9) and (10), a stimulus (R, G, B) in RGB space is converted to the value ($L^{abnormal}(s)$, $M^{normal}(s)$, $S^{normal}(s)$) in LMS space of protanomaly's color vision with the matrix $\mathrm{T}_{\mathrm{L}}^{\mathrm{abnormal}}$, which shows the relationship between RGB phosphor emission in the display and the L cone's response. To obtain the RGB value for the color vision of the protanomaly, the defected LMS values are reconverted to the RGB value ($R_{\mathrm{L}}^{\mathrm{defected}}(s)$, $G_{\mathrm{L}}^{\mathrm{defected}}(s)$, $B_{\mathrm{L}}^{\mathrm{defected}}(s)$) of normal color vision with the inverse matrix of $\mathrm{T}^{\mathrm{normal}}$.

Similarly, in the cases of deuteranomaly and tritanomaly, the stimulus (R, G, B) can also be changed into ($R_{\mathrm{M}}^{\mathrm{defected}}(s)$, $G_{\mathrm{M}}^{\mathrm{defected}}(s)$, $B_{\mathrm{M}}^{\mathrm{defected}}(s)$) and ($R_{\mathrm{S}}^{\mathrm{defected}}(s)$, $G_{\mathrm{S}}^{\mathrm{defected}}(s)$, $B_{\mathrm{S}}^{\mathrm{defected}}(s)$), respectively. They can be written as

$$\begin{bmatrix} R_M^{defected}(s) \\ G_M^{defected}(s) \\ B_M^{defected}(s) \end{bmatrix} = \begin{bmatrix} L_R^{normal} & L_G^{normal} & L_B^{normal} \\ M_R^{normal} & M_G^{normal} & M_B^{normal} \\ S_R^{normal} & S_G^{normal} & S_B^{normal} \end{bmatrix}^{-1} \cdot \begin{bmatrix} L_R^{normal} & L_G^{normal} & L_B^{normal} \\ M_R^{abnormal}(s) & M_G^{abnormal}(s) & M_B^{abnormal}(s) \\ S_R^{normal} & S_G^{normal} & S_B^{normal} \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{11}$$

$$\begin{bmatrix} R_S^{defected}(s) \\ G_S^{defected}(s) \\ B_S^{defected}(s) \end{bmatrix} = \begin{bmatrix} L_R^{normal} & L_G^{normal} & L_B^{normal} \\ M_R^{normal} & M_G^{normal} & M_B^{normal} \\ S_R^{normal} & S_G^{normal} & S_B^{normal} \end{bmatrix}^{-1} \cdot \begin{bmatrix} L_R^{normal} & L_G^{normal} & L_B^{normal} \\ M_R^{normal} & M_G^{normal} & M_B^{normal} \\ S_R^{abnormal} & S_G^{abnormal}(s) & S_B^{abnormal}(s) \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{12}$$

The goal of the color adaptation for anomalous trichromats is to compensate for the defected color information. The color adaptation is performed so that the defected RGB value is compensated completely, i.e., compensated color could be perceived the same as the original RGB value on the pixel color. From Eqs. (10)–(12), the corresponding defected color to an adaptation color can be written as

$$\begin{bmatrix} A\_R^{defected} \\ A\_G^{defected} \\ A\_B^{defected} \end{bmatrix} = [\mathrm{T}^{\mathrm{normal}}]^{-1} \cdot \mathrm{T}^{\mathrm{abnormal}} \cdot \begin{bmatrix} A\_R \\ A\_G \\ A\_B \end{bmatrix}, \tag{13}$$

where $[A\_R, A\_G, A\_B]^T$ is the adaptation color on the basis of pixel color.

The defected value ($A\_R^{defected}$, $A\_G^{defected}$, $A\_B^{defected}$) of the adaptation color can be made so that it is equal to (R, G, B). That means the anomalous trichromats could have visual accessibility equivalent to that of the normal trichromats. To do that, adapted stimulus (A_R, A_G, A_B) can be simply induced as follows:

$$\begin{bmatrix} A\_R \\ A\_G \\ A\_B \end{bmatrix} = [\mathrm{T}^{\mathrm{abnormal}}]^{-1} \cdot \mathrm{T}^{\mathrm{normal}} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}. \tag{14}$$

where $\mathrm{T}^{\mathrm{abnormal}}$ is one among $\mathrm{T}_{\mathrm{L}}^{\mathrm{abnormal}}$, $\mathrm{T}_{\mathrm{M}}^{\mathrm{abnormal}}$, and $\mathrm{T}_{\mathrm{S}}^{\mathrm{abnormal}}$ according to protanomaly, deuteranomaly, and tritanomaly, respectively. Then, the defected color ($A\_R^{defected}$, $A\_G^{defected}$, $A\_B^{defected}$) for the anomalous trichromat becomes equal to the original color (R, G, B). It means that the anomalous trichromats can see original colors.

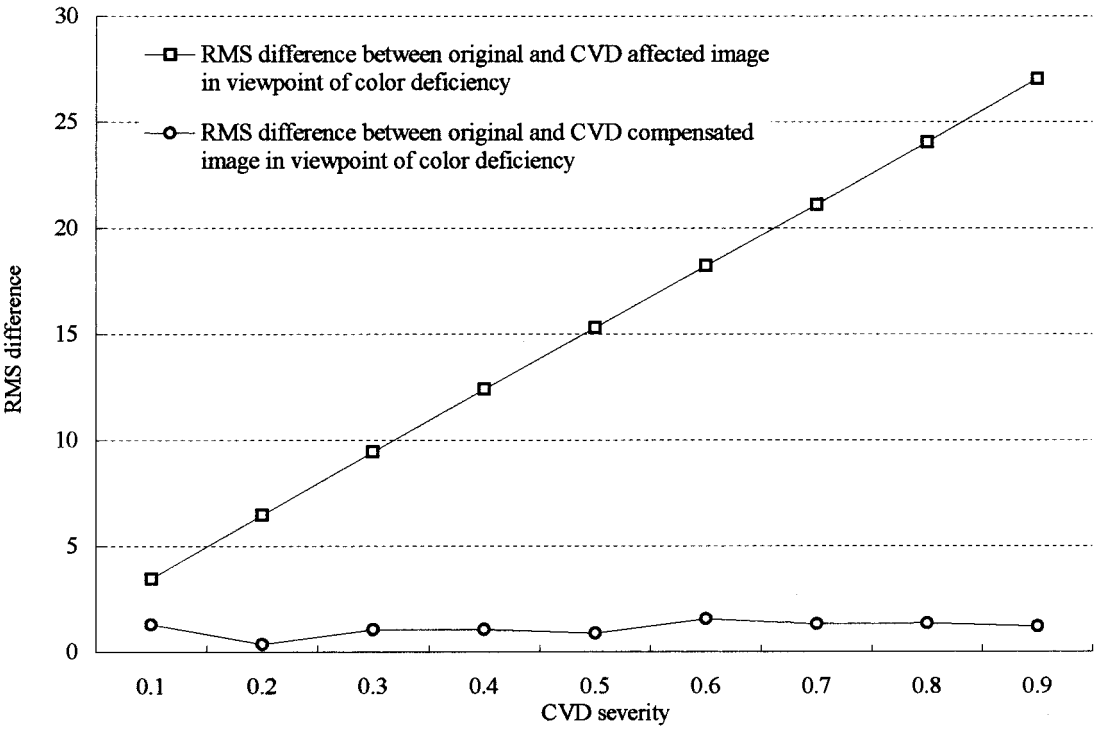

FIGURE 1. Color differences for CVD-defected image and CVD-compensated image vs. the severity of color deficiency.

III. EXPERIMENT

In this article, we performed experiments to verify the usefulness of the proposed method. The experiments were performed with quantitative and qualitative measurements. First, we measured a color difference between the adapted color and the original color in the viewpoints of the anomalous trichromats. We obtained an adaptation color based on the type and severity of an anomalous trichromat. Then, we simulated colors of both the original and the adaptation in the viewpoints of the anomalous trichromats, which we named CVD-defected image and CVD-compensated image, respectively. Finally, we measured the color differences of the two images: between the original image and the CVD-defected image, and between the original image and the CVD-compensated image.

For the measurements, we employed the root mean square (D) of the color difference. The color difference between the original image (I_o) and the defected image (I_d) in the viewpoints of the anomalous trichromats can be written as

$$D(I_o, I_d) = \sqrt{\frac{1}{H \times W} \sum_{k}^{H} \sum_{j}^{W} [\{I_o(k, j, r) - I_d(k, j, r)\}^2 + \{I_o(k, j, g) - I_d(k, j, g)\}^2 + \{I_o(k, j, b) - I_d(k, j, b)\}^2]}, \quad (15)$$

where k and j are the horizontal and vertical pixel position of the image, respectively; and r, g, and b are its RGB value. The root mean square is normalized by the height (H) and width (W) of the image.

Figure 1 shows the results for color difference from an original color. The test image was adapted with protanomaly (red deficiency) and severity degrees ranging from 0.1 to 0.9. As seen, the color difference of CVD-defected color from the original color increases as the severity is increased, whereas that of CVD-compensated color is quite small and independent of the severity.

We also conducted a subjective test of the proposed color adaptation. A qualitative measurement was performed with the anomalous trichromat to verify better color accessibility of the adaptation color.

We gathered subjects by color screening volunteers using the Ishihara test. Further we carried out HRR test (Hardy I. et al., 1954) and FM-100 Hue test (Farnsworth D., 1943) to obtain a more detailed diagnosis for the subjects who were identified as color defects with the Ishihara test. All tests were performed in the laboratory where the illumination condition was about 500 Lux. The subjects who participated in the test were found to be people with red and green deficiencies.

We performed the color adaptation using 8 test images. Colors on the test images were adapted based on color deficiency types and deficiency degrees from 0.1 to 0.9. The test images include natural image and man-made presentation material.

With two images (the original and the color-adapted images) on the display (CRT monitor; Samsung SM 950+), subjects were given questionnaires, which asked the subjects to detect confusion areas in the test images. For simplicity, we limited the subjects' responses to "better," "equal," or "worse," where the better cases showed that color-confused objects were more clearly discernable in the adapted image than in the

Table II. Experimental results with subject test

Image to be shown to Subjects	Number of Subjects who Answered			Number of Subjects
	Better	Equal	Worse	
1st	15	4	1	20
2nd	11	5	3	19
3rd	14	5	0	19
4th	14	5	0	19
5th	10	4	1	15
6th	10	5	4	19
7th	13	3	1	17
8th	8	7	2	17
Total number of subjects	95	38	12	145
Average number of subjects	11.875	4.75	1.50	18.125
Standard deviation of the number of subjects	2.475	1.165	1.414	1.642

original image, the worse cases showed that color-confused objects were less clearly discernable in the adapted image than in the original image, and the equal cases showed that the subjects' color discriminations on the test images were not quite different.

Table 2 shows the experiment results with qualitative measurement. The number of subjects who participated in the experiment was approximately 18 per image (mostly protanomaly and deuteranomaly). As shown in the table, on average, 11.875, 4.75, and 1.50 subjects responded "better," "equal," and "worse" on the color-adapted images, respectively.

IV. CONCLUSION

In this article, color adaptation for the anomalous trichromats was proposed to improve color accessibility for CVD people. General understanding of anomalous trichromats is modeled and described mathematically. An adaptation method was developed based on the model. Clinical experiments showed that the anomalous trichromats were able to recognize colors close to the original color with the adapted images. The proposed method was also quantitatively verified by measuring the color difference between the simulated original and adapted images. In conclusion, the proposed color adaptation method can provide better visual information in the image to the color-deficient people.

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