https://doi.org/10.2352/issn.2169-2629.2020.28.15

Analysis of Hue Circle Perception of Congenital Red-green Congenital Color Deficiencies Based on Color Vision Model

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Abstract

To investigate individual property of internal color representation of congenital red-green color-deficient observers (CDOs) and color-normal observers (CNOs) precisely, difference scaling experiment using pairs of primary colors was carried out for protans, deutans, and normal trichromats, and the results were analyzed using multi-dimensional Scaling (MDS). MDS configuration of CNOs showed circular shape similar to hue circle, whereas that of CNO showed large individual differences from circular to U-shape. Distortion index, DI, is proposed to express the shape variation of MDS configuration. All color chips were plotted in the color vision space, (L, r/g, y/b), and the MDS using a non-linear conversion from the distance in the color vision space to perceptual difference scaling was successful to obtain U-shape configuration that reflects internal color representation of CDOs.

Introduction

The idea of color universal design is spreading for the purpose of providing discriminable and comfortable colors to all people, especially for CDOs whose population is larger than 5% of males. To experience how CDOs perceive colors, various color-appearance simulations have been reported [1-3]. Not only to simulate color-perception of CDOs, but also to improve discriminability or preference, many attempts have been proposed employing color-compensation, enhancement, or recolorization in the field of color imaging [4-7]. These simulations or attempts for improvement are based on the color vision model of CDOs that their red-green opponent process is missing or weakened by the loss or spectral sensitivity shift of L or M cones. Some of the above studies proposed the way to explain individual differences of CDOs mostly based on the difference of spectral sensitivities of cones [8], but whether their models successfully explain real individual differences among CDOs are not yet indicated. It is widely known that there exist large individual differences for CDOs from strong dichromat to mild anomalous trichromat [9]. Furthermore, variations at color naming levels are more complicated [10-13]

Looking around color environment in everyday life, not a subtle difference in color appearance but a large color difference between objects seem more important to find out things or evaluate color images. In that sense, to investigate how primary colors are represented in the brain of CNOs and CDOs, which is called "internal color representation" in this study, is an essential issue for color universal design. In that sense, Shepard and Cooper's study [14] on similarity judgement is interesting. They showed that the internal color representation of CNOs expressed by the MDS configuration became circular similar to the hue circle of Munsell Color System, whereas those of CDOs became U-shape bending at turquoise and yellow. Unfortunately, they showed only the average data and variability of internal color representation among observers was not shown.

In this study, to investigate individual property of CDOs' and CNOs' internal color representation more precisely, we conducted difference scaling experiment for protans, deutans, and normal trichromats. An index to express the degree of distortion from circular shape in MDS configuration and a model to derive U-shape configuration based on the color vision model hitherto reported are proposed.

Experiment

We used 10 primary hues of the Munsell Color System with high and medium chroma in the experiment [15], but this study focuses on the results of high chroma colors of which Munsell notations are shown in Table 1. Alphabet(s) on the left side of Munsell notation indicates the name of each color chip in this study. All combinations of 10 color chips, i.e., 45 paired cards were prepared. Two color chips were put in the enclosure that was consisted of two opened 35mm slide mounts. Size of a color area was 2.5cm x 3.5cm and the two colors in a card were 2.5cm apart in each card.

Table 1. Munsell color notation (H V/C) of the test stimuli

Chroma Group			
R	**5R 4/14**	BG	**5BG 4/9**
YR	**5YR 6.5/14**	B	**5B 4/8**
Y	**5Y 8/14**	PB	**5PB 4/12**
GY	**5GY 6.5/10**	P	**5P 4/11**
G	**5G 4.5/10**	RP	**5RP 4/12**

Observer was asked to see the color card that was placed on a grey cloth covering the desk, and instructed to evaluate the difference of the pair using the scale of 1 (=Very close), 2 (=Rather close), 3 (=Neither close nor far), 4 (=Rather far), and 5 (=Very far). Surface of the desk was illuminated by a fluorescent light (CCT:5000K), and the horizontal illuminance at the color card was 560lx. Visual distance in the observation was 50cm. In addition to the color card experiments, we did similar difference scaling experiment using written color-name pairs without showing any color cards to observers. Results were indicated in elsewhere [16].

Ten protan, 10 deutan, and 10 normal color vision observers participated the experiment using high chroma color cards. All observers were examined for their color vision using Ishihara charts, panel D-15, and anomaloscope.

Results

Results of difference scaling obtained from the average of two trials were analyzed using non-metric MDS with Euclidean distance. The upper and lower rows of Figure 1 indicate the results of two different observers of CNO and CDO (protan), respectively. Two figures in the left and right in both rows are the results that indicate minimum and maximum DI, described later, in CNO and CDO (protan) groups, respectively. Most CNOs show circular shape similar to Figure 1 (a), but some show partly distorted shape. Whatever the shape is circular, elliptical, or partly distorted, test colors are arranged in the order of Munsell hue circle in the results of CNO. For protan, on the other hand, circular configuration is observed for only one protan as shown in Figure 1 (c) who was diagnosed as protanomalous. Most of protan observers show U-shape configuration bending at Y and PB similar to Figure 1 (d) of which observer was diagnosed as a protanope. To save the space, deutan results are not indicated here. One observer showed circular shape (Obs.D10), but others showed distorted shapes similar to the protan results.

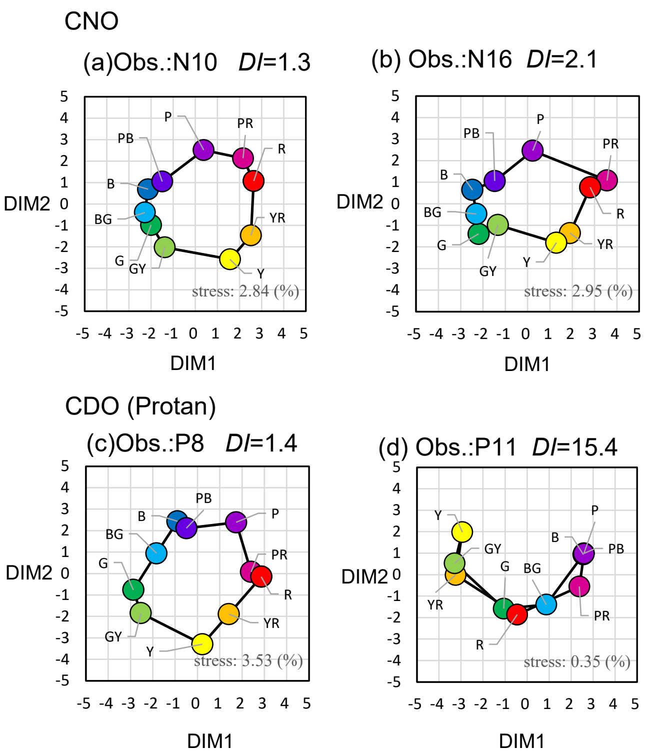

Figure 1. Results of hue circle estimation tested using high chroma cards for 2 observers from CNOs and CDOs (Protan).

Discussion

Distortion index

To compare the difference found in the shape of MDS configuration as shown in Figure 1, we propose the Distortion Index (*DI*) to express the degree of distortion from circular configuration of the MDS quantitatively as follows,

$$DI = \pi (d_{max}^2) / 4S \qquad (1)$$

where S and d_{max} denote the area enclosed by the lines and the farthest distance between plotted points in Figure 1, respectively. *DI* has a unit value when the MDS configuration is a circle and increases as it deviates from rounded shape. *DI* value of each observer is indicated above each figure. Values of these four observers so far correspond to apparent degree of distortion of MDS configuration for them implying that it is a good candidate for an appropriate indicator.

All observers' DI values are shown in Table 2. DI for CNO varies from 1.2 to 2.1, whereas that for CDO varies 1.4 to 15.4 for protan, and 1.3 to 14.7 for deutan, reflecting large variability of the shape of MDS configuration for CDOs. Based on all observers' data in this study, DI larger than 5.0

Table 2. Distortion Index of all observers

CNO		CDO			
		Protans		Deutans	
Obs.	DI	Obs.	DI	Obs.	DI
N10	1.3	P8	1.4	D10	1.3
N15	1.3	P7	2.0	D13	1.6
N17	1.4	P9	3.5	D11	2.9
N20	1.4	P10	3.6	D9	3.3
N32	1.4	P4	4.9	D17	5.0
N13	1.5	P5	5.9	D18	9.9
N11	1.6	P14	5.9	D8	11.3
N12	1.7	P3	7.4	D14	12.9
N14	1.8	P15	8.0	D7	13.9
N16	2.1	P11	15.4	D12	14.7

Simulation for MDS Configuration

We tried to estimate the MDS configurations of CNO and CDO based on the existing color vision model. Responses of luminance, red/green and yellow/blue chromatic channels, denoted as *L*, *r/g*, and *y/b*, respectively, are calculated using colorimetric values of test cards in the observing condition, and their spectral sensitivity functions of 3 channels employed in Yaguchi et al.'s study [3]. The cone opponent space in their study [3] is based on the cone fundamentals of CIE2006. They are shown in Figure 2. For protan, r/g function (dotted curve in Figure 2) was derived using the L cone spectral sensitivity function of which peak wavelength of spectral absorbance shifted +700cm^{-1}. We plotted test color chips in the (*L*, *r/g*, *y/b*) space, and the resulted points for CNO and CDO (protan) in r/g vs y/b plane are shown in Figure 3 (a) and (b), respectively. In order to simulate internal color representations, MDS configurations for CNO and CDO (protan) were obtained using the Euclidean distances in the (*L*, *r/g*, *y/b*) space between two color chips for all pairs. As shown in the figure, the result of

CNO is not a circle but rather oblique elliptical, whereas that of CDO is a thin ellipse compressed along the r/g axis. This simple calculation reproduces neither circular shape of CNO nor U-shape of CDO. To express U-shaped MDS configuration for CDO, some kind of elaboration is required.

Therefore, we introduce a partially non-linear conversion from the distance in color vision space to the difference scaling space as shown in Figure 4. It is the simplest saturation function that when the distance in color vision space is larger than a certain value, effective distance to derive MDS configuration does not increase any more but stays at a constant value. Conversion functions for CNO and CDOs are shown in Figure 4 are those obtained by searching appropriate value of the upper limit to best fit to the experimental data by trial and error. Ceiling values for CNO and CDO are 0.17 and 0.13, respectively. Using these conversion function, new MDS configurations are obtained for CNO and CDO as shown in Figure 5 (a) and (b), respectively. Simulation for CNO is still flat oval shape requiring some kind of additional elaboration, while that for CDO becomes U-shape similar to Figure 1 (d), indicating that the introduction of non-linear curve as shown in Figure 4 is effective to some extent. This suggests that direct outputs of (*L*, *r/g*, *y/b*) space is not enough to explain perceptual difference scaling which is thought to be judged in higher order process in the brain, but some conversion is needed.

Concluding Remarks

Internal color representation of CNOs and CDOs are investigated precisely by using the experimental results of difference scaling for 45 pairs from 10 primary color chips. First, the data were analyzed using the MDS, and distortion index, *DI*, is introduced to express the property of MDS configuration. Second, coordinates of all color chips in the color vision space, (*L*, *r/g*, *y/b*), were calculated using spectral sensitivities of the luminance, r/g, and y/b chromatic channels, and colorimetric data, to derive distance of each pair in the space. MDS configuration directly derived from the distances in the (*L*, *r/g*, *y/b*) space does not express the experimental results especially U-shape configuration for CDOs. Introduction of a non-linear function that saturates at a certain value in the conversion from the distance in the (*L*, *r/g*, *y/b*) space to the judgement of perceptual difference, is successful to derive the MDS configuration for CDOs. This might reflect the property of our color vision mechanism that the luminance, r/g, and y/b chromatic channels are thought to be in some intermediate level after LMS cones, while perceptual difference scaling is being judged at final stage of color vision in the brain, and some kind of non-linear conversion is needed between them. This study indicates how primary colors are internally represented in individual observers of different color vision types. A large individual variability especially for CDOs are clearly shown.

Non-linear conversion from elementary color vision space to perceptual difference scaling successfully explains the results to some extent. In order to develop effective color universal design in the field of color imaging, we need to seek more appropriate conversion function that can explain individual MDS configurations. Furthermore, to analyze the data using mediumly saturated color chips as well as color names is a future work to be done.

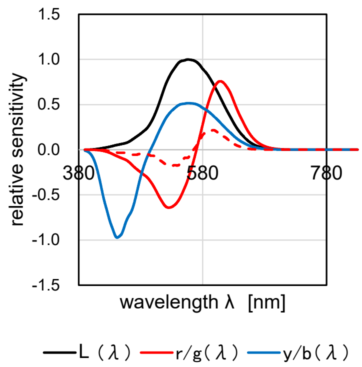

Figure 2. *Spectral sensitivity curves of luminance, red/green, and yellow/blue opponent color channels.*
Red line: CNO's r/g, Red dotted line: CDO's r/g.

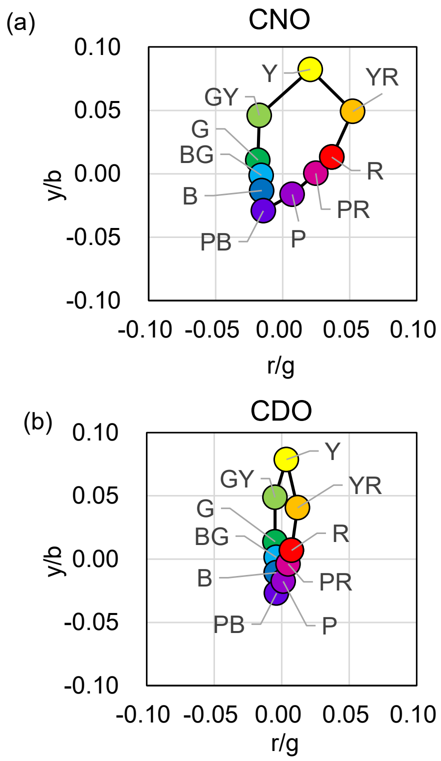

Figure 3. *Test stimuli plotted in r/g vs y/b plane for CNO (a) and CDO (b) color vision space.*

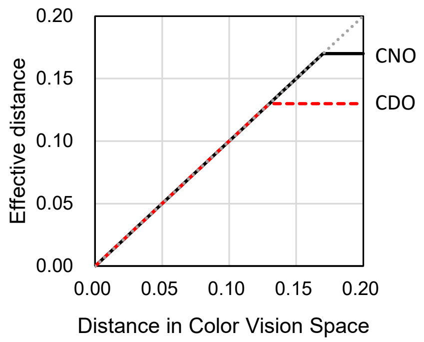

Figure 4. *Relation between distance in color vision space and effective distance.*

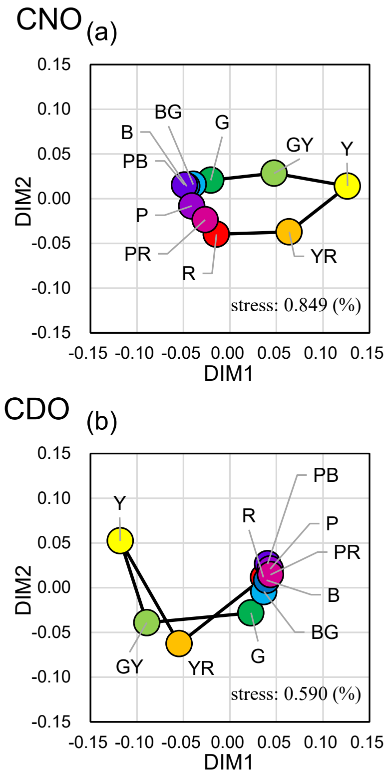

Figure 5. *MDS results without with the conversion using the relation shown in Figure 4 for CNO (a) and CDO (b).*

Acknowledgement

The authors would like to thank Color Universal Design Organization to their collaboration to carry out the experiment.

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