APPROACH TO COLOR APPEARANCE BY COLOR VISION DEFICIENT OBSERVERS

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Abstract

It is difficult for color vision defective (CVD) to discriminate some of color combinations, because of the lack of one or two types of cones. As known as color universal design, it is fortunately not so difficult to measure abilities of color discrimination on CVD and to work out countermeasures. It is the difficult and fundamental problem, however, to estimate color appearance on CVD. Because we do almost have no method to describe the color appearance directly at this moment, we have to use color names (or other descriptive words) to explain the color appearance. However, we cannot confirm that one color name means the same perception on each observer. Thus, in this paper, we tried one limited approach to investigate the color appearance on CVD, by color naming method in comparison with the data on color normal observers with color vision deficiency simulation glasses.

Recently, color is frequently used to present visual information in signs, displays, documents and so on. For examples, chromatic difference between neighboring colors, which depends on the ability of color discrimination, are used to highlight some parts of documents. Also, colors are used as one method of visual coding of different items, and typically this coding helps to find something quickly. It is difficult, however, for color vision defectives (CVD) to discriminate some of color combinations because on them, only one or two types of cones are actually working, instead of three types of cones on color-normal observers. It is caused by the fact that two types of cones in three types have the same or similar spectral sensitivities by genetic reasons, and the difference of the amount of signals from each type of cones should be too weak to be used as a chromatic signal for discrimination on some of colors. Thus, for universal access, confusing color combinations should be avoided in documents for CVD. This concept is called as Color Universal Design. Otherwise, information presented by color cannot be understood well by CVD. It means that in many cases unfortunately, the usage of color in the presentation prevents for CVD to understand it and it is even worse compared to the case that only black and white were used.

Thus, it is important for the Color Universal Design to know chromatic characteristics of CVD, especially about their performance of color discrimination and color appearance. Fortunately, it is not so difficult to measure abilities of color discrimination on CVD and to work out countermeasures. It is the difficult and fundamental problem, however, to estimate color appearance on CVD. Because CVD cannot discriminate some of colors, and/or because the strength of chromatic signals as the differences of the amount of each type of cones are much weaker compared with normal color vision observers, they may not understand names of colors used in color-coding and may put a different color name for a certain color. Thus, we should know about the color appearance of CVD. But, unfortunately, it is
very difficult to investigate this issue. We have to use color names (or other descriptive words) to explain the color appearance because we do almost have no method to describe the color appearance directly at this moment. But we cannot confirm that one color name means the same perception for all observers.

In this paper, we tried one limited approach to investigate the color appearance on CVD. We employed a color naming method and additionally compared the data on CVD with the data on color normal observers with color vision deficiency simulation glasses. The color vision deficiency simulation glasses, 'Variantor', is a functional filter in glasses type and was developed by authors and Ito Optical Industrial Co. Ltd. in order to simulate the ability of color discrimination of dichromats and to help Color Universal Design with the support of the Regional New Consortium Projects from the Ministry of Economy, Trade and Industry of Japan in 2005-2007. The glasses were planned to simulate only the ability of color discrimination, and results of color discrimination test (Cambridge Color Test) indicated the reasonable simulation performance for the purpose as shown in this paper. But, because the filter glasses were not initially planned to simulate the color appearance, we did not know whether the color appearance of color normal observers with the glasses would be the same with the color appearance of CVD. The opponent color theory by Brettel et al. (1997) predicted that because neutral color (white) should be neutral even on dichromats, the lack of L-cones or M-cones should mean the loss of red-green opponent channel and cause no response in both red and green. As shown in this paper, the color appearance of the color normal observers with the glasses are similar to the one expected by this theory.

Here, if the result of color appearance described by the color naming method would be similar between color normal observers and CVD, it would be a strong evidence that the color appearance of CVD is determined by the color opponent theory. However, the result of this paper unexpectedly indicated that the color naming by CVD is closer to the naming by color normal observers without the filter glasses rather than the color naming of them with the filter glasses. In terms of the color opponent theory, it is surprising that two dichromat (protan) observers in this paper used both red and green as the color name of some Optical Society of America (OSA) Color Chips, even though they could not discriminate red and green well. It suggested that the color appearance described by red and green in the color naming on CVD is different with the appearance on color normal observers. We discussed our hypothesis that CVD can separate red color chips from green color chips by lightness, even though the appearance in terms of hue is similar each other.

**Method**

*Subjects*

In this paper, we measured two abilities in color characteristics, those are color discrimination and color appearance. We tested the color discrimination on four color normal observers (two males, 21 and 43 years old and two females, 22 and 22 years old) and two dichromats (two males, 21 and 27 years old). As a measurement of the color appearance, we performed a color naming experiment on three color normal observers (three males, 21, 21 and 22 years old) and two dichromats (two males, 21 and 27 years old). Both of dichromats and one color normal observer (Male, 21 years old) joined in both experiments. Two dichromats are considered as a protanope from results of the color discrimination experiment described below. Also, color normal observers were checked by the color discrimination experiment. Observers' acuity was kept better than 0.7 by observers' own glasses or contact lens, even in the case of using the filter glasses.
Color Discrimination Experiment

Apparatus and Stimulus
For measurement of color discrimination, we employed the Cambridge Color Test (Cambridge Research Systems). A stimulus was presented on a CRT screen (FlexScan T566, Nanao) by the special graphic board for visual experiment (VSG2/4, Cambridge Research Systems) in 15 bits color resolution for each phosphor’s intensity (45 bits for RGB). A distance from an observer to the screen was 245 cm to make the spatial resolution of the stimulus higher. All apparatus and the observer were put in a dark room (Mean illuminance was 0.26 lux) to avoid the stray-light and effects of room illumination and the sunlight.

The stimulus for this test consisted of many small circles on the screen. Some of those circles are a set to make the C-shape target that has a slightly different color with other circles considered as a background. Observers answered an open position of the C-shape target, and thresholds of the chromatic difference between circles for the C-shape target and other circles as the background were measured. All circles had randomly 6 different luminance levels (8, 10, 12, 14, 16 and 18 cd/m²) in order to avoid the luminance artifact that can influence the real color discrimination. We used three chromatically different backgrounds to measure the direction of the chromatic change (called as a confusion line) in which color vision deficient observers cannot discriminate. CIE1931 xy coordinates of these backgrounds were (0.313, 0.330), (0.346, 0.407) and (0.280, 0.253). We measured thresholds for 20 different color directions from one background color. Threshold data from 3 sessions were fitted by one ellipsoid and the orientation of long axis of it was considered as the confusion line.

The CRT phosphors were calibrated spectrally using a spectroradiometer (CS-1000, Konia Minolta Sensing), while chromatic coordinates and luminance were measured with a chromameter (Konica Minolta Sensing, CS-200). The relation between phosphor radiance and voltage was linearized based on lookup tables generated using a photodiode and calibration software in the VSG software (Optical, Cambridge Research Systems).

Procedures
After 5 minutes light adaptation to the background white, a set of stimuli with one background color was presented one by one. Each stimulus was presented in 5 seconds and the observer answered the open position of the C-shape target by pressing one of four buttons. If the observer did not respond in 5 seconds after one presentation, we considered the answer as wrong. By a special staircase method (QUEST), the chromatic differences for each color direction were controlled and thresholds for each direction were determined. It took about 45 minutes for one session (15 minutes for each background color).

Color Naming Experiment

Apparatus and Stimulus
For color appearance measurement, we used a color naming method with an OSA color chip set (424 chips). We performed this experiment in a dark room with the special Xenon lamp illumination with a precise color temperature control (Artificial Sun Light 500W, Seric). The illuminance on a table covered by a grey sheet was 416 lux. With this illumination, the chromatic coordinates of the OSA white chip [4, 0, 0] was (0.324, 0.331) (5930 K in color temperature), and the luminance was 119 cd/m².

Procedures
After 5 minutes light adaptation to the illumination in the dark room, the observer answered names of color chips one by one in a random order. The observer could look at only one chip
at the same time on the table covered by a gray paper. Observers could use any color name freely, but the name had to be one word. Combination of color names (like blue-green) and usage of modifier (like dark gray or yellowish green) were not allowed. Observers performed this color naming experiment in 3 sessions on color normal observers and in 5 sessions on dichromats. If one observer used the same name on one color chip three times in 3 sessions (four or five times in 5 sessions), the name was considered as a stable name. As well known, some of color chips in a short distance in color coordinates had the same stable name that is called as categorical colors.

**Results and Discussion**

*Color Discrimination Experiment*

Figure 1 shows the results of the color discrimination experiment on one color normal observer (Female, 21 year old) without the filter glasses (a) and with the filter glasses (b). The size of one ellipsoid reflects thresholds of color discrimination from the background shown as the center of the ellipsoid and a larger ellipsoid means a lower ability of the color discrimination. As shown in Fig. 1, the filter glasses apparently made the ability of the color discrimination much worse on the color normal observer.

![Fig. 1](image1.png)

**Fig. 1.** Thresholds of color discrimination (denoted by small symbols) and color discrimination ellipsoids of one color normal observer (Observer HY, Female, 21 years old) without the filter glasses (a) and with the glasses (b). Thin solid curves around the data denote the spectral locus in CIE1931 chromatic coordinates and dotted lines denote a monitor gamut. Gray thick lines denote protan and dutan confusion lines as explained in panels.

![Fig. 2](image2.png)

**Fig. 2.** Same with the Fig.1 except the results of two dichromats (Observer HS, Male, 21 years old as (a) and Observer TT, Male, 27 years old as (b)).
Figure 2 shows the results of the discrimination on two dichromat observers (2 males, 21 and 27 years old). It is clear that the ability of color discrimination is much less on dichromats compared to the one on the color normal observer without the filter glasses. Because the orientation of long axes of the ellipsoids more match to theoretical protan confusion lines, we think these two dichromats are protanopes. From the comparison between Fig. 1(b) and Fig. 2, the filter glasses reasonably changed the ability of the color discrimination as like a dichromat, although the orientation of color confusion line is slightly shifted to counterclockwise from protan or dutan confusion lines. We confirmed by theoretical calculations that this shift of the orientation was caused by the characteristics of RGB phosphors of the monitor because the filter glasses was planned to work best for printing materials under the daylight (D65) and cannot necessarily be perfect for arbitrary illuminant lights.

**Color Naming Experiment**

The result of the color naming experiment was plotted in the coordinates of OSA color chips ([j, g, L]) with symbols denoting color names. Figure 3 shows the results of color naming on one color normal observer (Male, 21 year old) without the filter glasses (a) and with the filter glasses (b). The result of the color naming without the glasses in Fig. 1(a) is a typical one as showing areas of categorical colors. Color chips around (j, g) = (0, 0) were named as neutral colors (white, gray or black). Surrounding these neutral colors, chips were named as greenish colors (Green and Grass Green), Yellow, dark-yellowish colors (Brown, Skin color (HADA) and Ocher), Orange, reddish colors (Red and Pink), Purple and bluish colors (Blue and Watery Blue) in clockwise. The color names measured with the filter glasses on the color normal

![Fig. 3. Color names of 424 OSA color chips plotted in [j, g, L] space on one color normal observer (Observer TW, Male, 21 years old) without the filter glasses (a) and with the glasses (b). Larger symbols mean that 3 responses in 3 session or 4-5 responses in 5 sessions for each chip were the same. Smaller symbols mean 2 or 3 responses for each case. Small black dots denote that responses were not stable. Circles denote neutral colors (Black(black symbols), Gray (light symbols) and White(open symbols)). Upward-pointing triangles denote green (dark) and grass green(black). Downward-pointing triangles denote red(dark) and pink(light). Right-pointing triangles and left-pointing denote Yellow and bluish colors (Blue(dark) and Watery blue(light)), respectively. Diamonds denote dark-yellowish colors (Brown(dark), Skin color (light) and Ocher(half dark)). Squares and pentagrams denote Purple and Orange.](image-url)
observer matched well with theoretical expectation from the ability of the color discrimination. Because colors of chips aligned in parallel to g-axis are roughly on protan and dutan confusion lines, these color chips would be hardly discriminated each other. Also, it was theoretically expected that the number of color chips named as red or green would be much reduced. As shown in Fig. 3(b), areas of categorical colors were shaped vertically along to g-axis. There was almost no color chip named as reddish colors (Red or Pink), and the number of chips named as greenish colors was reduced.

Figure 4 shows the results of color naming on two dichromats (protnopes) (2 males, 21 and 27 years old). There are some interesting differences between color normal observers with the filter glasses (figure 3(b)) and dichromats. Firstly, although color vision deficient observers cannot discriminate between red and green well, they still use both of them in color naming. Results indicated, however, that dichromats have less number of categorical colors because some categorical colors were combined to one category; green & gray, pink & skin color, watery blue & purple, and purple & pink. We consider that these differences are caused by the difficulty of color discrimination along the red-green direction in the color coordinates. Also, we should expect that by using some cues like difference of lightness, dichromats still can answer the color names of red and green color chips correctly. Secondary, the number of chips named as neutral colors was much reduced on dichromats. This fact can mean that the theoretical expectation that neutral color should be neutral even on CVD should not be a strong binding condition because neutral colors are not common in the color appearance of dichromats.

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