Categorical Color Perception of Color Normal and Deficient Observers

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Color changes as a continuous variable. We can discriminate millions of colors, but at the same time we categorize colors into discrete color names. Dichromat (color deficient) observers also categorize colors in manners very similar to that of color normal (trichromat) observers despite the fact that color deficient observers confuse many colors. In this study, we investigated characteristics of categorical color perception of trichromat and dichromat under various chromatic illuminations. Observers named 424 OSA uniform color samples using only the Berlin and Kay's eleven basic color terms. Categorical color perception of normal trichromat was found to be robuster under strong chromatic illuminants than dichromats. Dichromats could utilize a lightness cue to name indistinguishable colors. It is unlikely that dichromats have the same categorical color mechanism as normal trichromat has. The present results support that there is the physiological substrate for categorical color perception specific to trichromat or dichromats.
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1. Introduction

Our environment is full of colors. We can perceive millions of colors so that we can detect, discriminate and recognize objects. We also utilize colors for signs, marks and other artificial objects. We enjoy colors in our everyday lives. Thus, color perception is one of the most important functions in our visual system. It is quite common for us to ask how many colors there are in a scene. By the phrase of "how many" we involuntarily assumes that we can count colors. It is said, for example, that there are seven colors in the rainbow (Fig. 1). This expression would be somehow strange because the rainbow is actually a light spectrum in which wavelengths change continuously. Each wavelength appears different in color and, consequently, colors change continuously with wavelength. Therefore, color should not be counted as discrete objects. In fact, however, we actually count colors. This means that we perceive colors as being continuous, but at the same time we perceive colors as being discrete so that we can count numbers of colors. We have discrete color perception. We can combine continuous color appearances into a single category and call it with a color name. In other words, we divide the whole color continuum into some discrete categories. This color perception is called categorical color perception.

Figure 2 shows a human color-vision model for normal trichromat. At the first level, L, M, S cones in the retina catch photons of the light-spectrum with three different spectral sensitivities, that is, long, middle and short wavelength regions in the light spectrum. L, M, S cones yield three responses. These responses are added or subtracted in three cone-opponent channels, two chromatic (r/g and y/b) channels and an achromatic (w/b) channel. The opponent-color signals reach a higher level in the cortex, in which continuous color signals are transformed into discrete signals. Many psychophysical and physiological studies suggest that there might be categorical color mechanisms, which are real substrates existing in a higher

level, to make discrete responses.[1–3] This is why we can easily attach color names to continuous color appearances. Berlin and Kay proposed eleven basic color terms, i.e., red, green, yellow, blue, brown, orange, purple, pink, gray, white, black. We might have eleven basic categorical mechanisms corresponding to the eleven basic color terms.[4] On the contrary it might be the case that we somehow arbitrarily divide continuous colors into some parts and assign color names to them. Some investigators support the idea that there might be no concrete mechanism yielding discrete responses.

The majority of us are categorized into the normal trichromat. Since the trichromat has three kinds of cones, i.e., L, M, S cones, colors are represented in a three-dimension space. Some people are categorized into dichromats. Dichromats lack a type of three cones, and are classified into three groups, i.e., protanope, deuteranope and tritanope, depending on L, M, and S cone lacked in the retina. For dichromats colors are represented in a two-dimension space. The protanope and deuteranope are the most common dichromats, but the tritanope is extremely rare.

All colors, represented in a three-dimension color space, are well discriminated by a trichromat, but some colors are not discriminated by dichromats. The Protanope and deutranope cannot discriminate colors, such as red, yellow, and green, on a confusion line. Because they do not discriminate red, yellow and green it is assumed that they cannot use red, yellow and green, and that their color names should be limited to yellow, blue, white, black, and gray. However, they actually use color names of red, yellow, and green in their everyday lives as a normal trichromat does. This is quite curious and interesting. How do they manage to use color names that they do not discriminate, such as red, yellow, and green?

Many previous studies reported that dichromats could use trichromat-like categorical color names. Boynton and Scheibner reported that red, yellow and green hue names were used by dichromats in color naming to monochromatic

Fig. 1.   (Color) A picture of rainbows. We can count numbers of colors in a rainbow.
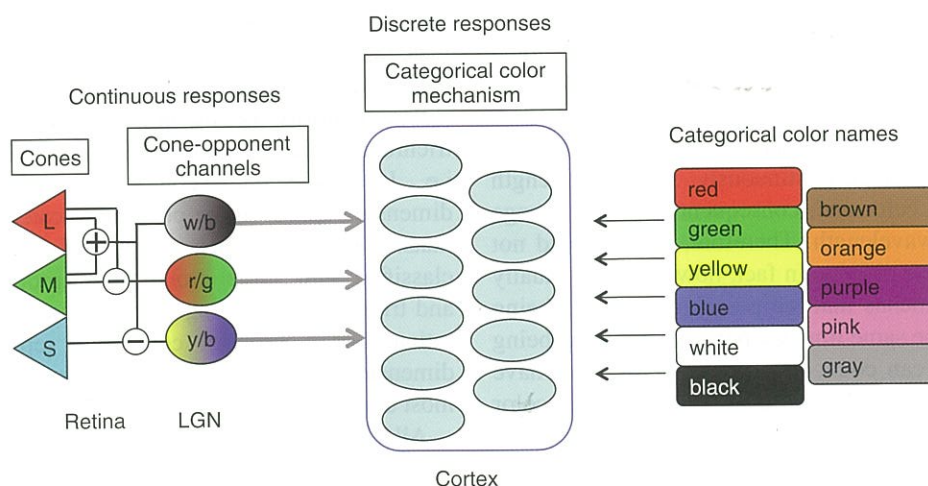

Fig. 2.   (Color) A human color-vision model for normal trichromat.

lights.[5] Jamson and Hurvich tested dichromat's usage of color names by Panel D-15 test.[6] They showed that a normal trichromat used similar names for perceptually similar colors, but dichromats used dissimilar names for perceptually similar colors, and that color names used by dichromats well corresponded to those of a normal trichromat, suggesting that dichromats did color naming in a different manner from that of a trichromat. Montag and Boynton, Montag, and Uchikawa et al. showed trichromat-like categorical color names by dichromats.[7–10] Wachtler, et al. reported that hue scaling by dichromat was similar to that by a trichromat, and proposed a non-linear neural model to account for dichromat's color naming.[11] These previous studies suggested that dichromats used additional responses made by rod, anomalous third cone[7,8] or anomalous non-linear neural channel.[11] It has also been suggested that dichromats might use differences in lightness (lightness cue) to name colors with the same $y - b$ value. Nishida et al. reported that dichromats could perform trichromat-like categorical color naming for real color chips, but their performance was degraded by using a monitor to present color stimuli, and even worse with small-field and brief-

duration.[12] They also showed that dichromats confused color names on the red–green direction when the stimuli were presented in equal-luminance condition. Their results clearly indicated that dichromats could somehow use luminance (lightness) of color chips as a critical visual cue to perform trichromat-like categorical color naming.

In this study we aimed at investigating characteristics of categorical color perception of trichromat and dichromats under various chromatic illuminations. It is well known that our visual system is endowed with the color constancy ability in order to recognize objects in various illuminant conditions. To achieve color constancy the visual system must separate illuminant color and surface color from the reflected light. If dichromats use some visual cues, appearing on the surface of a color chip, for the categorical color naming it would be more difficult for them to perform the color naming task under a chromatic illuminant since the chromatic illuminant might mask the visual cues. If this would happen dichromats could not hold the categorical color constancy in the same way as trichomat does. The questions here are how robust the trichromat and dichromats hold categorical color perception under different chromatic illuminations. If we will find differences in color categorizations by the trichromat and those by dichromats these differences may reveal some aspects of the mechanism for categorical color perception per se.

2. Methods

2.1 Stimulus and apparatus

We used the OSA uniform color scales as stimuli [Fig. 3(a)]. They are 424 color chips, consisting of 13 lightness levels. In Fig. 3(a), color chips with two consecutive lightness levels are shown in the same panel except those of $L = -7$. The color chips are arranged at equal color-difference interval on the j–g plane. The j-axis is a horizontal axis, approximately representing yellow–blue direction, and the g-axis is a vertical axis, approximately representing green–red direction.

Test illuminants we used were a white light of 6500 K and three chromatic illuminants chosen on the daylight locus, i.e., 3000, 6500, and 25000 K. Other three illuminants were Red and Blue primaries of the LC projector. Their spectral power distributions are shown in Fig. 3(b). When the OSA color chips were illuminated by these test illuminants the chromaticity coordinates of the color chips changed according to test illuminants. Figure 3(c) shows the CIE 1931 (x, y) chromaticity coordinates of all OSA color chips under the test illuminants. It should be noted that the chromaticity points of the color chips spread widely for 25000, 6500, and 3000 K illuminants, but they concentrated into small areas for Red and Blue illuminants.

An OSA color chip was mounted in a gray envelope (6 cm × 6 cm, 5.8° × 5.8° in visual angle) with a circular hole of 2.5 cm (2.4°) diameter, through which the observer looked at the color chip. The color chip was put on the center of a desk (40° × 50°). The desk was cover with a gray paper. A LC projector illuminated the color chip from above.

2.2 Procedure

In an experimental session the observer adapted to a test illuminant for 3 min in a dark booth before the session started. The illuminance was 500 lx on the desk. After adaptation the observer started to randomly select a color chip from a set of 424 OSA color chips by his hand. Then he named color of the color chip with Berlin and Kay's 11 basic color terms, i.e., white, black, red, green, yellow, blue, brown, orange, purple, pink, gray. The viewing distance was 59 cm. All 424 color chips were named twice.

2.3 Observers

Two normal trichromat observers, three protanope observers and two deuteranope observers participated in this experiment. The normal trichromat observer was tested with Ishihara plates. The dichromat observers were tested with Ishihara plates, Panel D-15, the anomalo-scope. They also had the gene examinations (except YY) and the number of gene in exon 4,5 was one. With all these color vision tests they were diagnosed as congenital (or strong) protanope or deuteranope.

3. Results and discussion

3.1 White illuminant

The categorical color naming results are shown for a normal trichromat SN in Fig. 4. The test illuminant was 6500 K white. Symbol colors represent color names the observer used to the OSA color chips in the first trial (larger symbol) and in the second trial (smaller symbol). It is shown that the OSA color space was well divided into 11 color categories by SN. We used centroids of chromaticity coordinates to characterize the location of the basic colors in the OSA color space (Fig. 5). The centroid was calculated by averaging the coordinates of all the color chips named with the same name weighted by 2 (when consistently named) or 1 (when inconsistently named). In Fig. 5, colors of each symbol represent color categories. The size of the symbol is proportional to the number of the color chips named for that color name. It is noticed that the centroids for SN uniformly spread in the j–g and the j–L planes. The other normal trichromat MM showed similar results.

Figure 6 shows the centroids obtained under the 6500 K white illuminant for all observers. Protanope KS shows a well-separated centroid distribution in the j–g plane, which is similar to that of normal trichromat SN. Deuteranopes TF and HH have quite similar centroid distributions to SN and KS although their ranges are smaller. Protanopes AY and YY have centroid distributions compressed along the r–g direction. They tend to spread along a line, meaning that AY and YY did not show trichromat-like categorical color naming even when the illuminant was white although they used all color names that normal trichromat used. These findings imply that individual differences in categorical color naming by dichromats are larger than previously reported.

3.2 Chromatic illuminants

Figure 7(a) shows the centroid distributions for normal
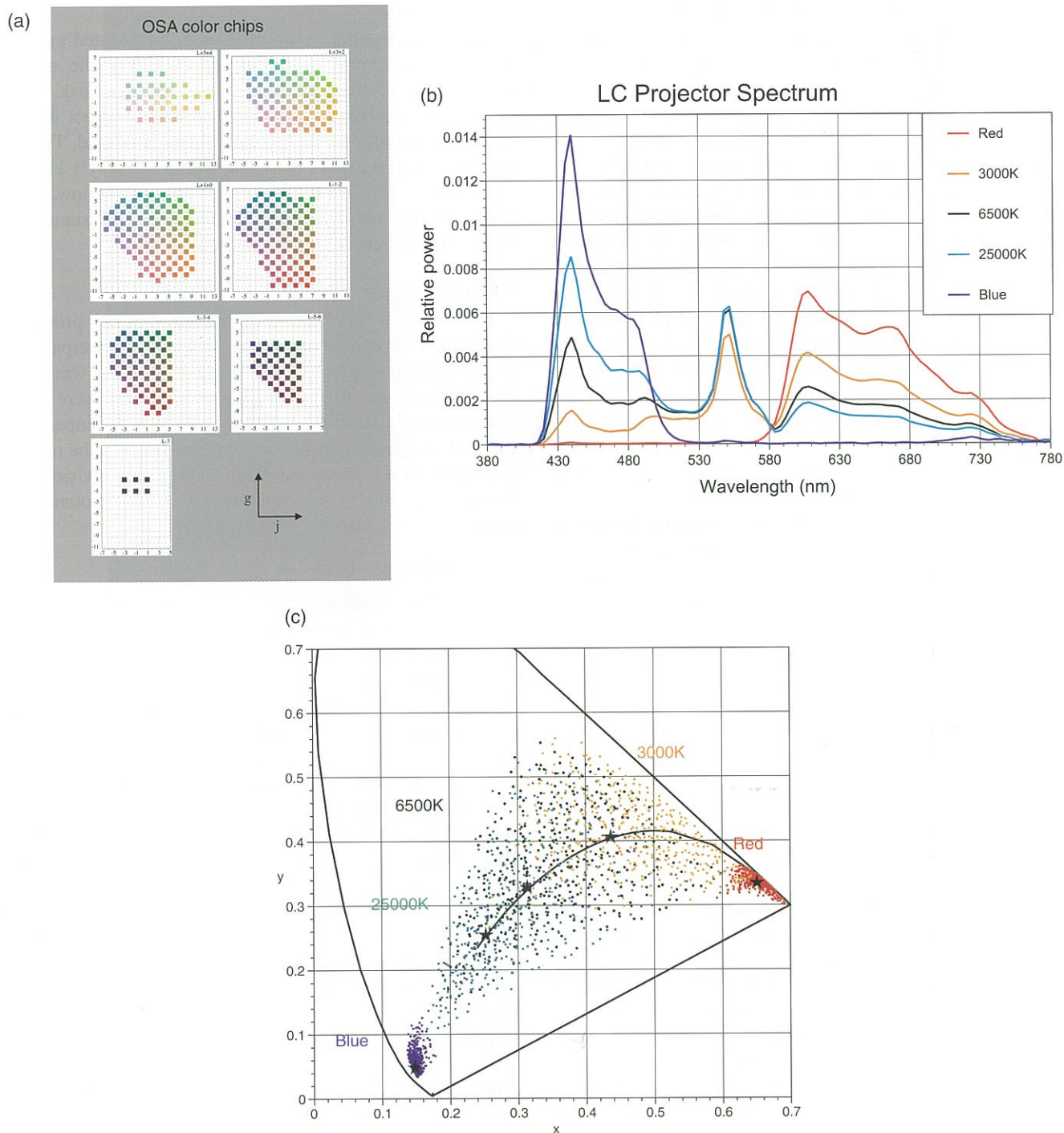
(a)

(b)

(c)

Fig. 3. (Color) (a) OSA uniform color scales. (b) Spectral power distributions of illumimamts, Red, 3000 K, 6500 K, 25000 K and Blue. (c) CIE 1931 (x, y) chromaticity coordinates of all OSA color chips under each test illuminant.

trichromat SN under chromatic illuminants. They appeared almost invariant across all illuminants, meaning that SN had good color constancy. Figure 7(b) shows the centroid distributions for protanope KS. These distributions shows that KS has also good color constancy almost the same as SN.

Figure 8 shows that centroid distributions of deuteranopes TF and HH for 3000 and 25000 K are quite similar to those for 6500 K. However centroids for Red and Blue are found compressed in the r–g direction, being in alignment with dotted lines shown in Fig. 8. This distribution tendency is similar to that of protanopes AY and YY under 6500 K in Fig. 6.

3.3 Analysis in LMS cone space

In Fig. 9, the color naming data, shown in Fig. 4, are replotted in the LMS cone space. Colors of symbols represent color categories of normal trichromat SN obtained under the
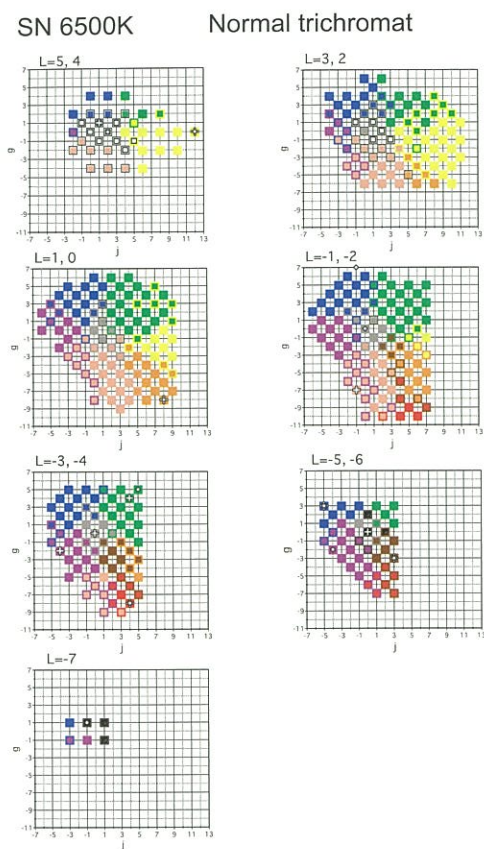
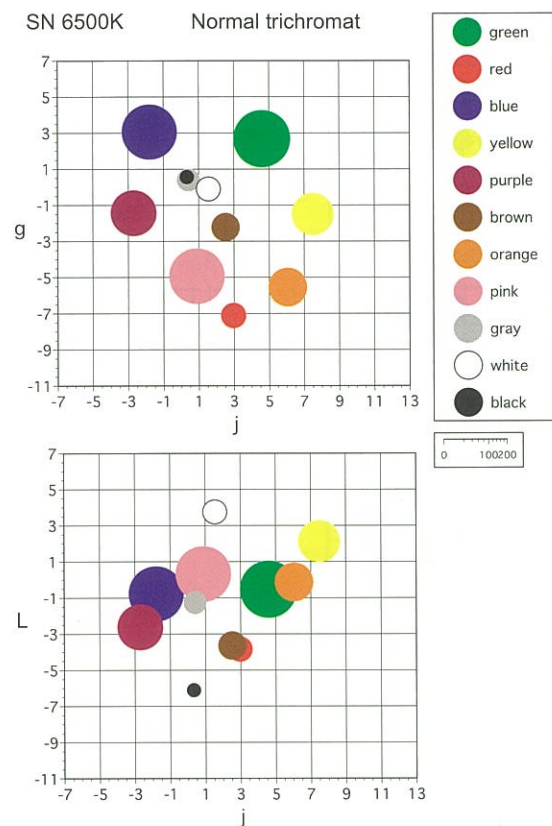Fig. 4. (Color) Categorical color naming results for normal trichromat SN. Test illuminant: 6500 K.

Fig. 5. (Color) Centroids of chromaticity coordinates of all the color chips named with the same name weighted by 2 (when consistently named) or 1 (when inconsistently named). Observer: normal trichromat SN, Test illuminant: 6500 K.
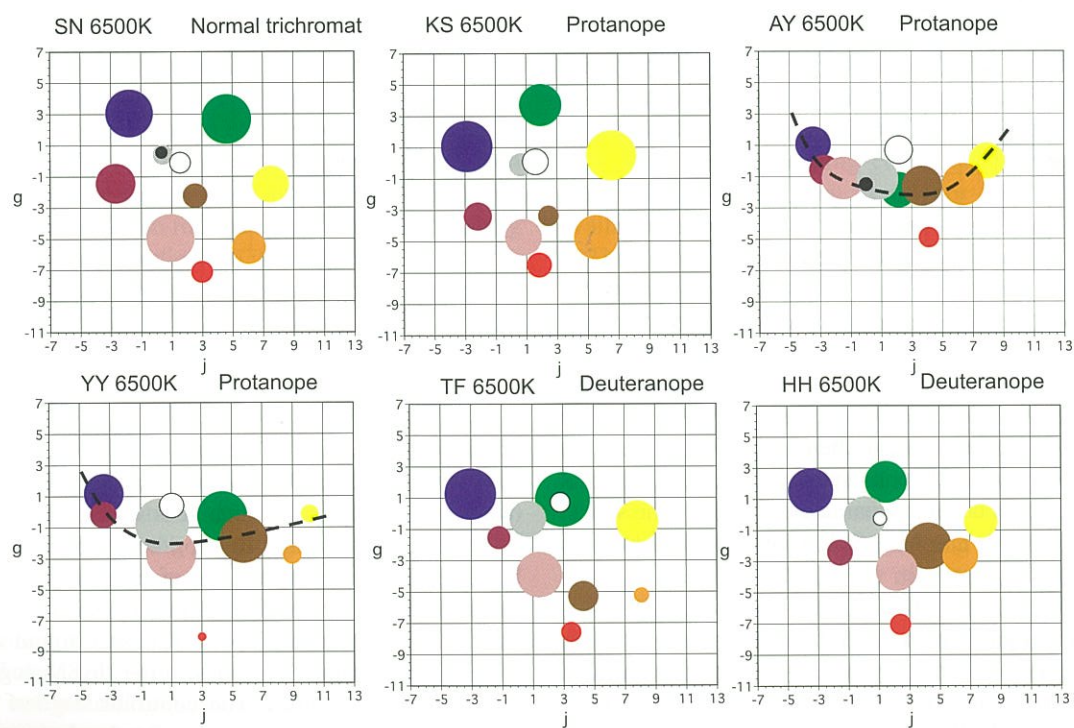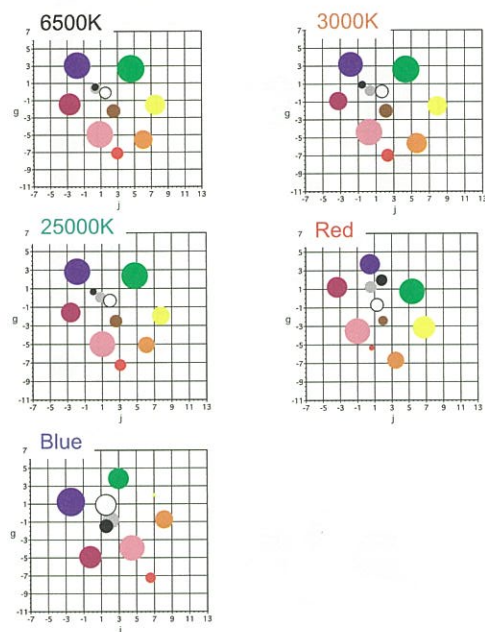

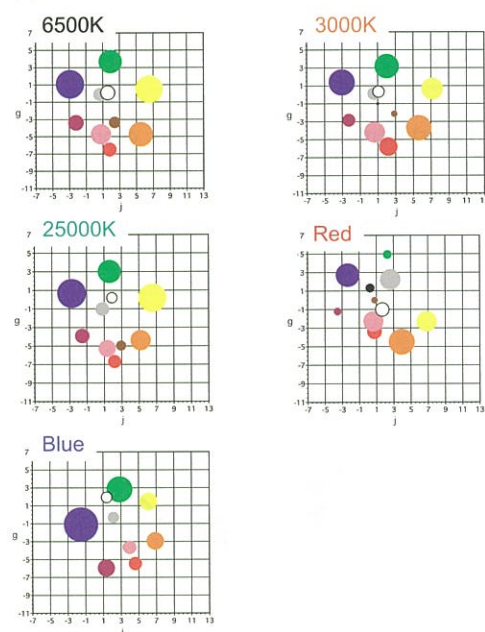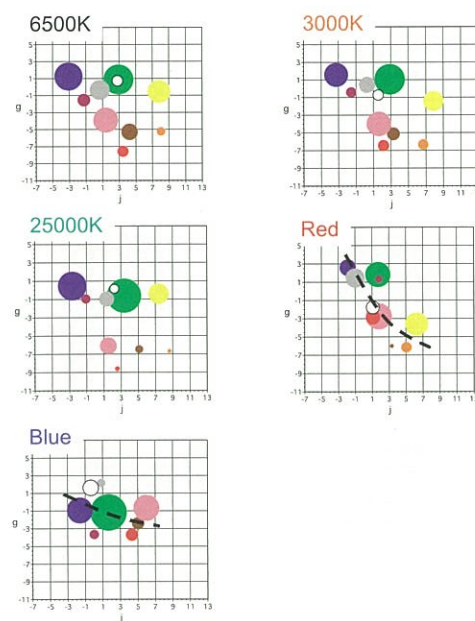Fig. 6. (Color) Centroids obtained under the 6500 K white illuminant for all observers.

Fig. 7. (Color) Centroid distributions for (a) normal trichromat SN and (b) protanope KS under chromatic illuminants.

Fig. 8. (Color) Centroid distributions for (a) deuteranope TF and (b) deteranope HH under chromatic illuminants.

6500 K white. It can be seen that the color categories are not separated in any of the 2D cone spaces, (L, S), (M, S), and (L, M). They should be well separated in the 3D cone space, for example, $(L - M, L + M - S, L + M + S)$, which is the opponent-color $(r - g, y - b, w - b)$ space.

It was shown in Fig. 6 that centroids of protanopes AY and YY were aligned with each line and some of them overlapped with other centroids in the j–g plane. It is curious why AY and YY could use different color names to those overlapping centroids. We plotted the OSA color chips in the (M, S) cone space to know whether categorical color names
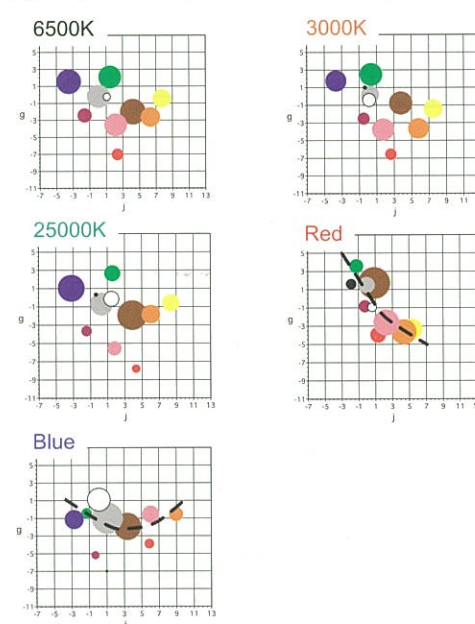
obtained by AY and YY could be separated in the (M, S) color space. We used the $(\log M, \log S)$ space instead of the (M, S) space to plot the data. This was because it was easier to see all points in the log–log scale than the liner scale. Figure 10 shows distributions of color names of the OSA color chips and centroids of color names in the $(\log M, \log S)$ cone space. The color chips of AY were found well divided into the basic color categories in the $(\log M, \log S)$ plane as shown by dashed lines. The centroids are not overlapped, indicating that they can be separated using lines. YY had similar results. Thus, AY and YY had categorical regions
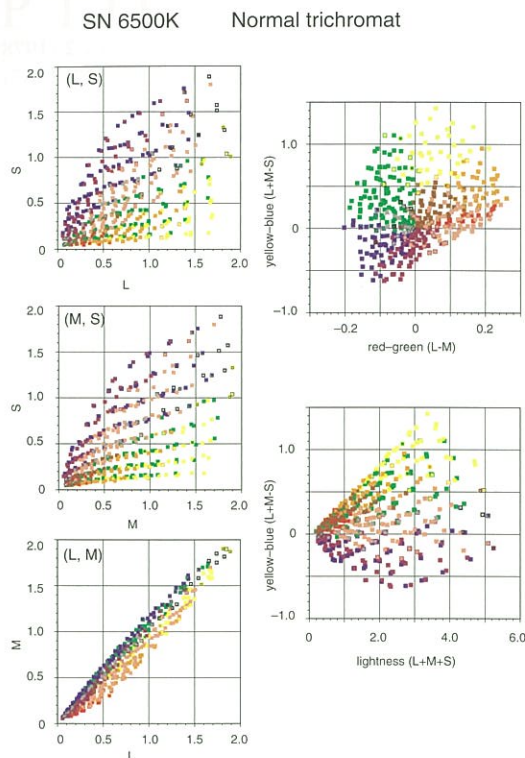
Fig. 9. (Color) Categorical color naming data for SN, 6500 K shown in the (L, M, S) cone space, and the (L − M, L + M − S, L + M + S) opponent-color space.

Fig. 10. (Color) Distributions of color names of the OSA color chips and centroids of color names in the (log M, log S) cone space for AY, 6500 K and YY, 6500 K. The color chips of AY and YY were found well divided into the basic color categories in the (log M, log S) plane as shown by dashed lines.

well separated in the 2D (M, S) cone space. In the (log M, log S) graph the positive diagonal line corresponds to the lightness direction. In fact, color names of white, gray and black were obtained on the diagonal line in Fig. 10. The upper region from the diagonal line (log S > log M) should correspond to the blue region, and the lower region from the diagonal line (log M > log S) should correspond to the yellow region. AY and YY used blue, pink and purple in the blue region along the lightness direction, and yellow, green and red in the yellow region along the lightness direction. Brown and orange was also found in the yellow region along a line approximately vertical to the lightness direction. This vertical direction should correspond to the saturation direction. All these findings suggest that AY and YY might mainly use lightness and partly use saturation of the color chips to name them.

4.　General Discussion

Categorical color perception of normal trichromat was found very robust under strong chromatic illuminants, which means that there must be the physiological categorical color mechanism. Dichromats can utilize lightness or other weak cues to name indistinguishable colors so that their color naming is consistent with that of normal trichromat.

In Figs. 7 and 8, it is noticed that protanope KS shows quite good categorical color constancy even in the Red and Blue illuminant conditions similar to that obtained by 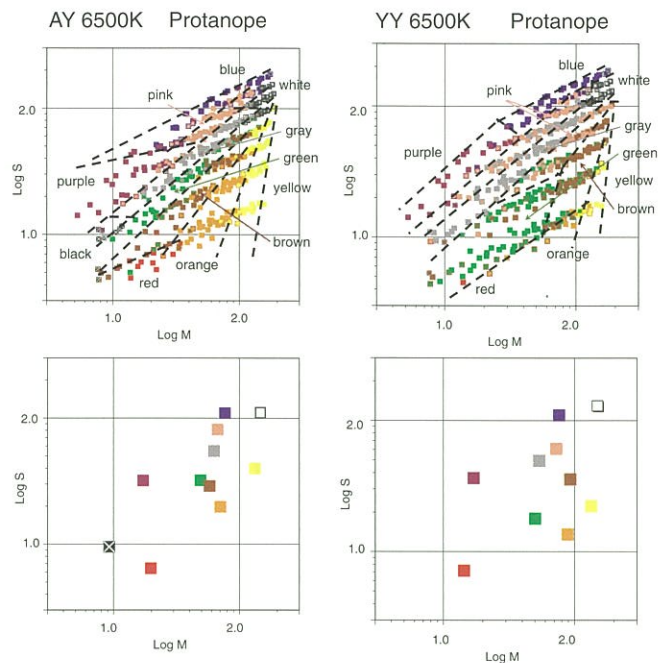normal trichromat SN. However, deuteranopes TF and HH shows poor categorical color constancy in the Red and Blue illuminant conditions, which is different from that of SN. When the data obtained by TF and HH in the Red and Blue conditions in Fig. 8 were plotted in the (log L, log S) space, like in the (log M, log S) space for protanopes AY and YY in the white condition, we obtained good categorical separations similar to those of AY and YY although the graphs are not shown here. These suggest that TF and HH might change their strategies for naming colors under strong chromatic illuminants because they could not use the visual cues available in normal circumstances.

Therefore, it is unlikely that dichromats have the same categorical color mechanism as normal trichromat has. Dichromats seem to assign color names to the color continuum in their particular individual manners, which normal trichromat does not necessarily adopt. If it is the case that normal trichromat somehow arbitrarily divide continuous colors into some parts and assign color names to them, and that there is no concrete mechanism yielding discrete categorical color responses, we would expect larger individual differences in color naming by normal trichromat, just like we observed in color naming by dichromats in this study. Therefore, again, it is supported that there is the physiological substrate for categorical color perception.

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