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Change of Color Appearance in Photopic, Mesopic and Scotopic Vision

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Mesopic vision describes a range of light levels where vision is mediated by both cones and rods. The appearance of color in mesopic vision differs drastically from that in photopic vision, where only cones mediate visual information. We used a haploscopic color matching technique to investigate the color appearance under various illuminance levels, ranging from photopic to scotopic via mesopic levels. The observers did color matching between a test color chip under various illuminance levels and a matching color stimulus presented on the Cathode-Ray Tube (CRT) display under the photopic illuminance condition. The results showed that not only chroma and lightness but hue of most color chips changed with illuminance. The manner of the hue changed depended on the color of the test chip, while matching points approached a neutral gray with decrease in illuminance level for all test chips. Chroma reduced continuously with decrease of the illuminance level until 0.1 lx for reddish and yellowish color chips or until 1 lx for greenish and bluish ones. Beyond those illuminance levels, chroma was approximately constant. Lightness decreased with decreasing illuminance level for all test chips except bluish color chips, for which lightness did not decrease much in general and even increased in some cases as predicted by the Purkinje shift. The experimental results obtained in the present study provide critical features that should be considered in predicting the appearance of color at low light levels.

Key words: photopic vision, mesopic vision, scotopic vision, color appearance, color matching experiment

1. Introduction

The dynamic range of human visual system covers a wide illuminance range from 10^5 lx to 10^{-3} lx. This wide dynamic range is achieved with the two kinds of photoreceptors in the retina: cones and rods. Cones are active at high illuminance level and contribute to color vision, but absolute sensitivity is low. Rods are active at low illuminance level and have high sensitivity, but do not contribute to color vision directly (no color is perceived when only rods are active). Vision may be classified simply as of two types: photopic or cone vision and scotopic or rod vision. However, there are illuminance levels where both cones and rods are active and the vision at these levels is called mesopic vision. Color appearance in mesopic vision differs from that in photopic vision and is not easily estimated only from knowledge of photopic and scotopic vision. To predict a color appearance in mesopic vision, it is necessary to determine the interactions between cone and rod signals at the levels of mesopic vision.

Several color appearance models[1)] have been developed to predict the appearance of colors under different illuminations. However, their target is the color in photopic vision and most of them cannot be applied to low illuminance levels. Prediction at low light levels is important in many applications. For example, the prediction of color appearance is useful in designing a night or evening environment. It is important for safety to know how children's clothes appear at night. Another application field may be in film making, where one might want to convert daytime scenes to an evening or night scene using digital imaging techniques. A color appearance model for mesopic vision can be used for these purposes.

There are a number of studies in the literature on color appearance in mesopic vision. These studies[2–12)] have revealed the existence of interaction between cones and rods concerned with color vision. For example, in a number of experiments Stabell and Stabell[3–7)] showed that rods influence color perception, and found that the change of rod activation in the adaptation field altered the color appearance of both long and short wavelength lights. The color changes can be summarized as rods contributing to both redness and blueness. Similarly, Buck and his colleagues[8–11)] have shown that rods influence not only blue but other hues (i.e., they produce a red-bias at unique blue, a blue-bias at unique green and a green-bias at unique yellow). To coordinate these results, they proposed a model of non-linear rod influence on color vision. These studies provided enough data to conclude that rods influence both red/green and yellow/blue opponent color perception, although data to construct a quantitative model are insufficient. Without serious consideration of rod influence on hue perception, several studies characterized the change in color appearance in mesopic vision.

Viénot *et al.*[13)] reported a simulation using a model based on the Hunt 94 color appearance model.[14)] The model predicts chroma reduction with decrease of illuminance level, which is asymmetric between the red/green and yellow/blue color opponent channels (more severe in red/green). Similarly, Pattanaik *et al.*[15)] proposed a model based on the adaptation and spatial frequency characteristic of color vision and applicable to a wide range of illuminance levels. Their model also predicts general characteristics of color appearance in mesopic vision, while acknowledging rod influence on color vision is necessary for accurate prediction of the mesopic color appearance.

Previous studies[16,17)] in our laboratory reported color matching experiments with a large number of color chips that provided sufficient data for accurate prediction of mesopic vision. Based on the color matching results using the Natural Color System (NCS) color atlas as matching stimuli, Yaguchi *et al.*[16)] proposed an empirical method to predict color appearance in mesopic vision with an accuracy

of 4 ~ 5 in the CIELAB ΔE_{ab}^*. Unfortunately, it is difficult to use the results to convert other device independent color spaces. The NCS color chips are not related with XYZ color space by any mathematical formula and spectral reflection is required to convert the NCS color to other spaces. In the method proposed by Yaguchi *et al.*, interpolation or extrapolation of color notation in the NCS space must be followed by conversion to XYZ color space assuming spectral reflection of the color chips to use them in other spaces. This is not only inconvenient but may cause large error due to an untrue spectral reflection. There is another possible problem in the experiment by Yaguchi *et al.* Since they used a number of color chips in the NCS color atlas as matching stimuli, the precision of the matching result may have been restricted by the color differences between the color patches in the atlas.

In this study, we estimated the color appearance of chips covering large color regions under various illuminance levels using a haploscopic color matching technique with a computer controlled display. For ease of application and modeling, the data were obtained in terms of the CIE *XYZ* tristimulus values. This provided quantitative data with a wide range of stimulus colors, which are required to build a quantitative model in mesopic color vision.

2. Methods

A haploscopic color matching technique[18] was employed to measure the corresponding colors of test color chips under various illuminance levels. The observers saw a test color chip with their left eye and adjusted the appearance of the color presented on a Cathode-Ray Tube (CRT) display with the right eye so as to match the appearance of the test color. The illuminance conditions for the left and right eyes were controlled independently in terms of a separation dividing the booth into two rooms, so that each eye was exposed to an illuminant condition controlled independently. Since we used different illuminance conditions between the test and matching stimuli, the observer had to do asymmetric matching.

2.1 Apparatus and stimuli

The inside walls of the booth were covered with gray paper, whose CIE color coordinates were approximately the same as those of N5 in Munsell notation. The test color chip was presented in the left room of the booth under one of the six illuminance levels. There were 15 fluorescent lamps simulating D65 on the ceiling of each half of the booth. The matching stimulus was generated on a CRT display set behind the booth and the observer saw the color through an aperture. The illuminance level of the matching field (right eye) was fixed at 1000 lx. The illuminance of the test field (left eye) was either the illuminance level of 1000, 100, 10, 1, 0.1 or 0.01 lx; each level was realized by adjusting the number of lamps and ND filters. Selection of the locations of the lamps allowed us to control the illuminance level with precision higher than that predicted from the number of lamps.

The test stimulus was one of 48 color chips (JIS standard color system, which is equivalent to the Munsell color system). There were 45 chromatic and 3 achromatic color chips with various Munsell values and chroma approximately equally spaced in hue angle (see Fig. 1 and Table 1). These 48 chips included more colors with high chroma than the previous studies.[16,17] The matching stimuli were generated on a 21" CRT display (SONY Multiscan G500) controlled by a video card (VSG, Cambridge System) with 15 bit intensity resolution for each phosphor. The CRT display was calibrated by a spectroradiometer (MINOLTA CS-1000). The test and matching stimuli were both 10 × 10 deg squares, with rods which would contribute to color perception. Three males and two females with normal color vision participated in the experiments, their ages ranging between 22 and 33. Observers JS and KK wore clinically prescribed soft contact lenses, and NM wore glasses. All observers had sufficient practice at the task before the experiments began.

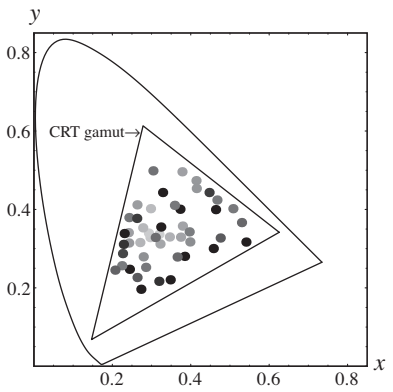


Fig. 1. The chromaticities of 48 test color chips on *xy*-chromaticity diagram with the gamut of the CRT for matching stimulus.

Table 1. 48 test color chips

No.	Color chip	No.	Color chip	No.	Color chip
1	10.0Y 8/10	17	5.0RP 4/8	33	10.0BG 9/3
2	7.5Y 8/8	18	2.5RP 6/10	34	10.0BG 5/6
3	5.0Y 5/4	19	10.0P 4/12	35	7.5BG 7/6
4	2.5Y 6/8	20	7.5P 8/4	36	5.0BG 4/6
5	10.0YR 7/10	21	5.0P 4/12	37	2.5BG 8/4
6	7.5YR 5/8	22	2.5P 6/8	38	10.0G 6/8
7	5.0YR 7/14	23	10.0PB 5/10	39	7.5G 5/6
8	2.5YR 8/4	24	10.0PB 3/12	40	5.0G 7/8
9	10.0R 6/14	25	7.5PB 7/6	41	2.5G 8/6
10	7.5R 7/6	26	5.0PB 4/10	42	10.0GY 6/10
11	5.0R 6/12	27	2.5PB 6/8	43	7.5GY 5/6
12	5.0R 4/14	28	10.0B 9/3	44	5.0GY 8/10
13	2.5R 8/6	29	10.0B 5/8	45	2.5GY 7/4
14	10.0RP 4/10	30	7.5B 8/4	46	N9
15	7.5 RP 7/8	31	5.0B 5/6	47	N6.5
16	5.0RP 8/4	32	2.5B 7/6	48	N1.5

2.2 Procedure

Both eyes were in the dark before each session. The

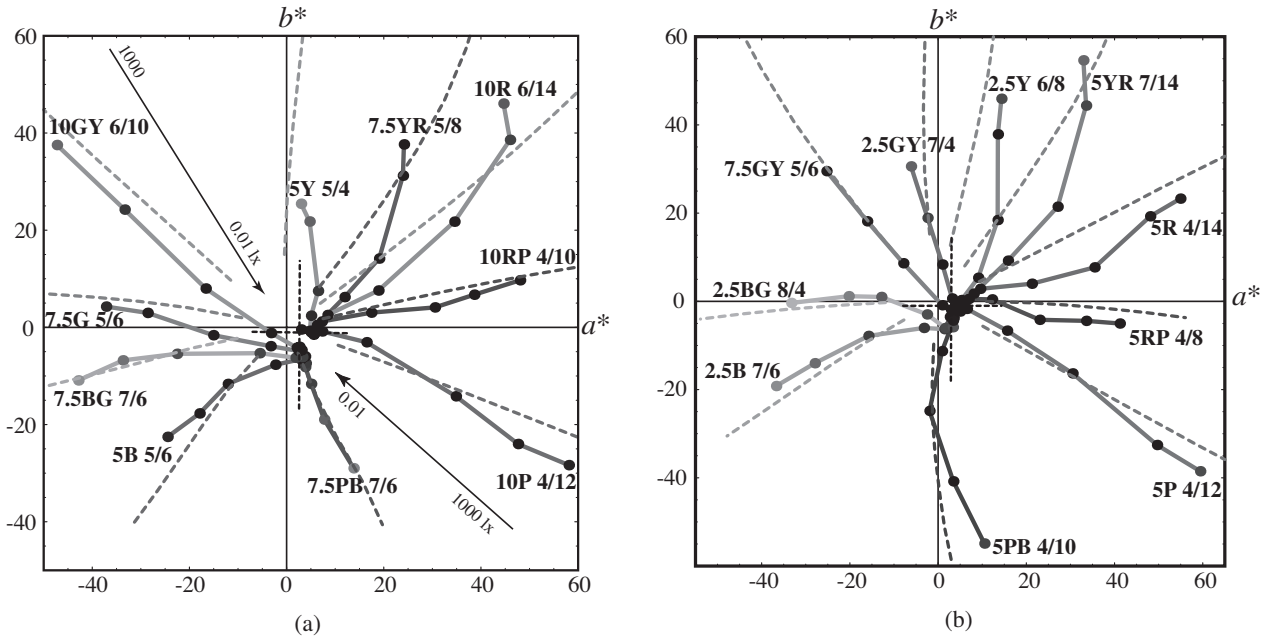


Fig. 2. Changes in color appearance of 20 test chips approximately equally spaced in hue angle in the CIELAB color space, (a) shows one half and (b) shows the other half. Dashed lines indicate the loci of constant hue and chroma of the Munsell renotation system. The center of the dashed cross indicates the matching point to N5 under 1000 lx.

period of the dark adaptation was 15 min under high illuminance level conditions (1000, 100, 10 lx) and 30 min under low illuminance level conditions (1, 0.1, 0.01 lx). A preliminary experiment showed that the dark adaptation period of 15 min was sufficient under the high illuminance level conditions. After the dark adaptation, left and right eyes were exposed to each illuminance level for 5 min for light adaptation, and then observers adjusted the chromaticity and the luminance of the matching color so that it appeared the same color as the test color chip. The color matching was replicated sequentially three times for each test chip individually. All data were obtained in terms of CIE *XYZ* tristimulus values and the mean value of the three matchings was calculated for each observer. The results were then converted to the coordinates in CIE 1976 $L^*a^*b^*$ color space.

3. Results

We present the results averaged for all observers for hue, chroma and lightness, respectively. The features of the results described below are also seen for individual observers.

3.1 Hue

Figures 2(a) and (b) show the change in color appearance of 20 test chips approximately equally spaced in hue angle, in the a^*b^* plane of the CIELAB color space as a function of illuminance level. The origin corresponds to the color of the illumination in the matching room determined from CIE *xy* coordinates measured at the stimulus location. Although the origin ideally corresponds to neutral gray, the actual matching point for the N5 under 1000 lx (assumed to be the neutral gray) was slightly off this point as indicated by the center of the dashed cross in Figs. 2 and 3.

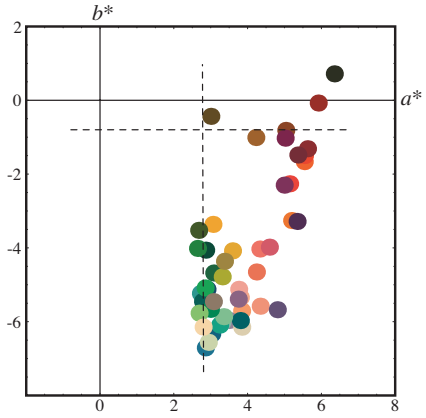


Fig. 3. The matching points at 0.01 lx of all test chips at the CIELAB color space. The color of each symbol corresponds roughly to the color of each test chip. The center of the dashed cross indicates the matching point to N5 under 1000 lx.

Figure 3 shows the matching points at 0.01 lx for all test chips. All the matching points plot close to the neutral gray point (the center of the dashed cross). However, the matching points at 0.01 lx did not seem to distribute around the neutral gray isotropically but instead appeared to be bimodal. One set of the data distributed around the point (3, −5) and another set distributed around the point (5, −1). This suggests the existence of color perception at 0.01 lx. If there were no color seen at the level, the matching point should compact at the coordinates of the neutral gray independently on the test color chips. The results showed some variation from the simple prediction. The source of

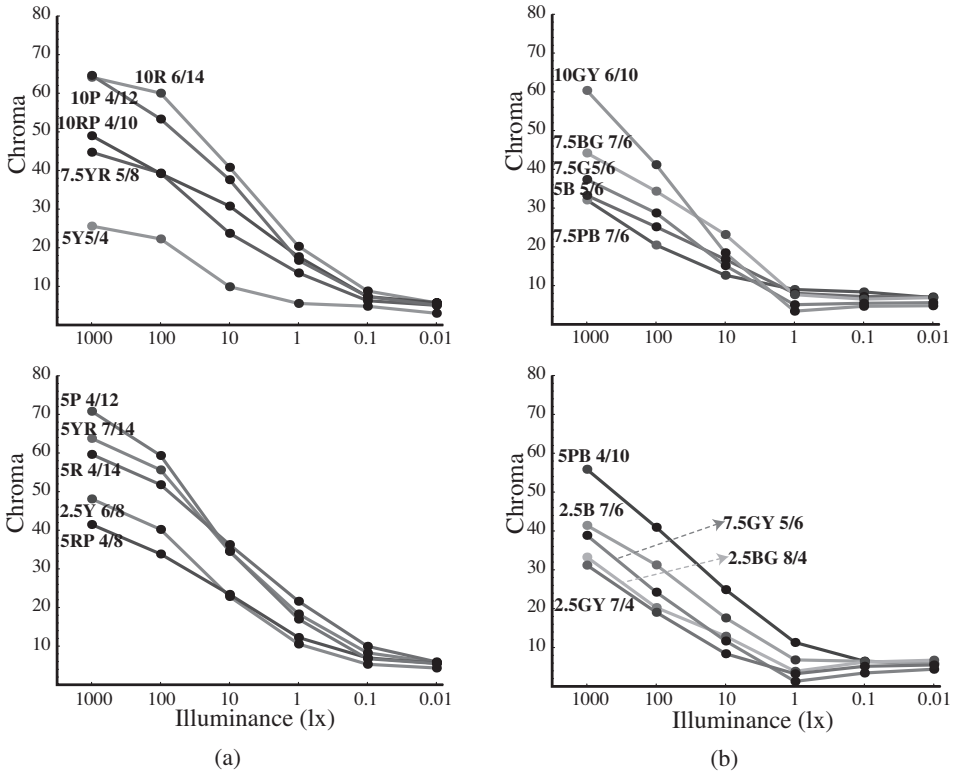


Fig. 4. Chroma changes of test chips as a function of illuminance level, (a) is for reddish and yellowish test chips and (b) is for greenish and bluish test chips.

color at 0.01 lx is perhaps signals from L-cones and rods since these two are likely to have higher sensitivity than the other photoreceptors. This is supported by the fact that the lightness of the color chips at this level could be predicted from the rod spectral sensitivity function or $V'(\lambda)$ except for reddish color chips. The bimodal-like distribution shown in Fig. 3 also supports this notion. The matching points at 0.01 lx around (5, −1) are for reddish color chips, or color chips with reflectance of long wavelength lights. Activation of L-cone should shift the color appearance to the positive a^* direction.

Another difference among different color chips was in hue shift. The loci of matching color on the color coordinates were not straight on the a^*-b^* coordinates for many of the test color chips, indicating that hue shifted with the change in illuminance level. Although the hue may shift with change in chroma, the change of hue angle in our results is more than the hue shifts due to chroma change. This can be recognized if the data are compared with the loci of constant hue and chroma of the Munsell renotation system in the a^*-b^* coordinates[19] as shown by dashed curves in Fig. 2.

Figure 2 shows that the manner of the hue shift differs among color chips of different hue. The hue shifts for different color chips are summarized below.

Y, YR, R, RP and P color chips: The loci bend toward a^* axis or the reddish direction with decrease in illuminance level above 1 lx, beyond which the loci are relatively straight. The matching points at 0.01 lx distribute around (5, −1).

PB, B and BG color chips: The loci bend toward the greenish direction with decrease in illuminance level above 1 lx, beyond which the loci are relatively straight. The matching points at 0.01 lx distribute around (3, −5).

G and GY color chips: The hue angles of the matching points for these chips are approximately consistent and the points at 0.01 lx distribute around (3, −5) as do those for PB, B, and BG color chips.

3.2 *Chroma*

Figure 4 shows the chroma of the matching color in CIELAB color space as a function of illuminance level. The manner of chroma change is also different among chips of different color. A large decrease of chroma is seen between 100 and 0.1 lx for reddish and yellowish color chips (Y, YR, R, RP and P) as shown in (a) and between 1000 and 1 lx for greenish and bluish ones (PB, B, BG, G and GY) as shown in (b). The decline of the chroma with decrease of the illuminance level finishes at about 0.1 lx for reddish and yellowish color chips while at about 1 lx for greenish and bluish ones. After the decline, chroma is approximately constant at a value around 5 in both cases. The shift from photopic vision to scotopic vision appears to finish at higher illuminance levels for greenish and bluish color chips than for reddish and yellowish ones as far as chroma is concerned.

3.3 *Lightness*

Figure 5 shows the lightness of the matching color as a

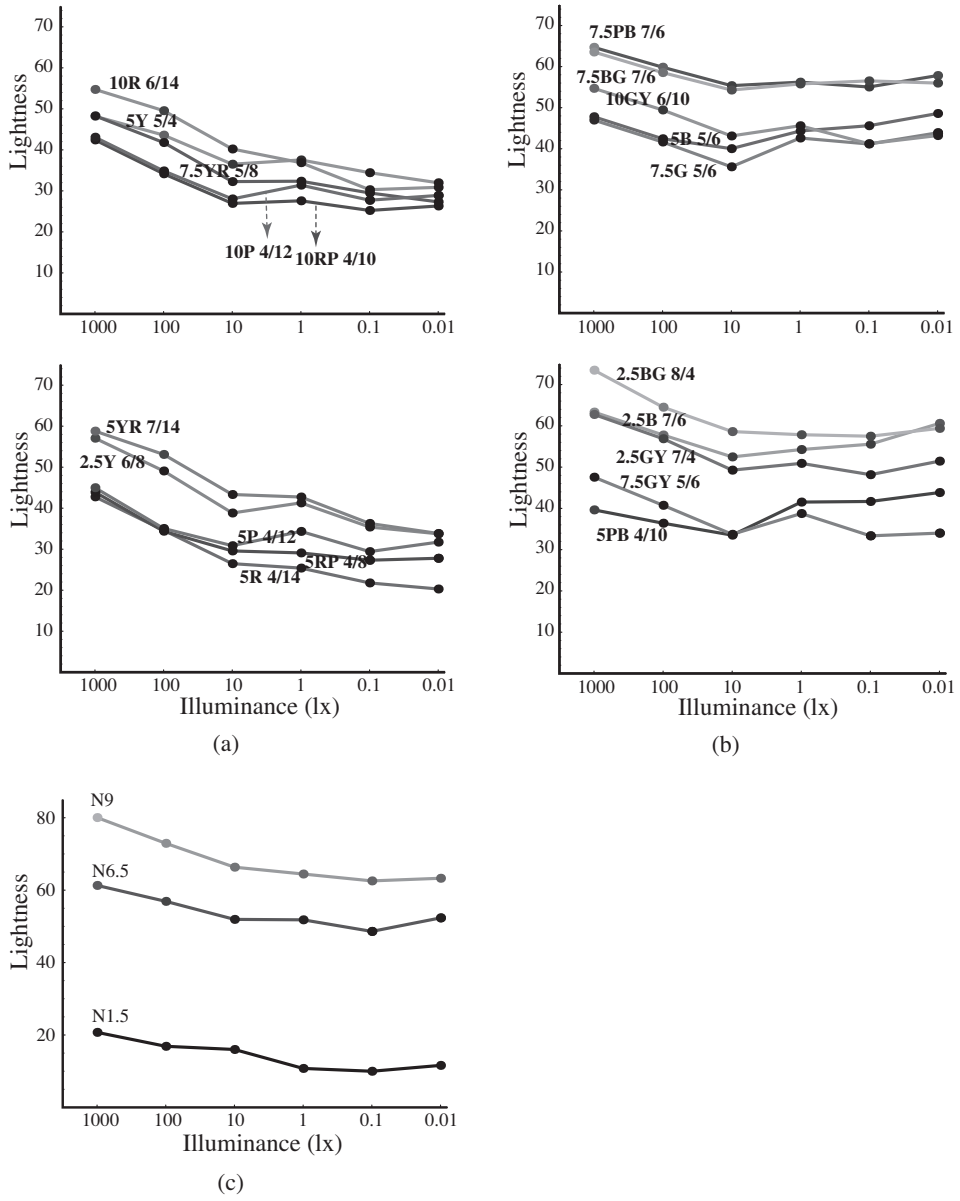
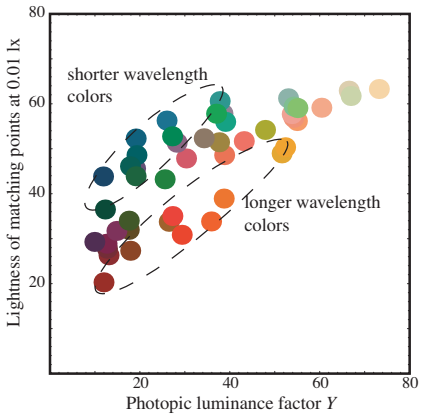


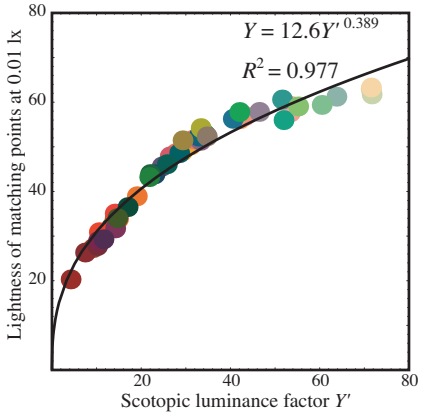
Fig. 5. Lightness changes of test chips as a function of illuminance level, (a) is for reddish and yellowish test chips, (b) is for greenish and bluish test chips and (c) is for achromatic chips.

function of illuminance level. Lightness is the relative luminance of matching color to the white luminance of the CRT display (100 refers to the white). The functions of the lightness changes for different color chips can be divided into two groups, dependent on whether the lightness increases or not at the illuminance levels of mesopic range (Fig. 5(a) and (b)). The lightness for the reddish and yellowish color chips monotonously decreases with decrease in illuminance level up to a level between 10 and 0.01 lx depending on test color. The lightness for the greenish and bluish color chips shows a minimum between 10 and 1 lx after the decrease with luminance level and then the lightness increases with further decrease in illuminance level. The increase is prominent in B, PB color chips as expected from the Purkinje shift. Figure 5(c) shows the lightness change of the achromatic color chips with illuminance level. The degree of lightness change through the illuminance level for the achromatic colors is less than for the other colors. Among the three chips, N9 test chip showed the largest reduction of lightness when the illuminance changed from 1000 lx to 0.01 lx, which decreased lightness range at 0.01 lx.

Figure 6(a) shows the relationship between photopic luminance factor of 48 color chips and lightness of matching points at 0.01 lx. If the cone system determines the lightness, the data should be on the line with slope 1. Figure 6(a) shows that lightness of the greenish and bluish color chips scattered above the line of the shorter wavelength whereas that of the reddish and yellowish color scattered close to the line of the longer wavelength. This indicates that greenish and bluish chips appear to be lighter at 0.01 lx than at 1000 lx, which is referred to as the Purkinje shift. Figure 6(b)



(a)



(b)

Fig. 6. (a) Relationship between photopic luminance factor Y and lightness of matching color at 0.01 lx (100 corresponds to white). (b) Relationship between scotopic luminance factor Y' and lightness of matching color at 0.01 lx. Color of each symbol corresponds roughly to the color of each test chip in both (a) and (b).

shows the relationship between the scotopic luminance factor and the lightness of matching points at 0.01 lx. The plot shows a monotonic relationship between the scotopic luminance calculated with $V'(\lambda)$ and perceived lightness. This suggests that the rod signal determines the lightness of color chips at 0.01 lx, and that the relationship between the perceived lightness and rod signal is nonlinear. Since lightness in terms of the relative luminance to white is a linear function of photopic luminance by definition, the nonlinear relationship in Fig. 6(b) should reflect the nonlinear relationship between the achromatic scales in photopic vision and scotopic vision. The relationship can be expressed by a power function as shown here.

4. Discussion

We measured the corresponding color of the color chips under various illuminance levels from photopic to scotopic levels and found that the hue, chroma and lightness of the chips changed with illuminance and the manner of the color change depended on test patch colors. The general tendencies of our empirical results are consistent, in terms of the changes in three perceptual attributes (i.e., lightness, chroma and hue) with illuminance levels, with those found in the previous study[16,17] by our laboratory. Two of the three major findings are consistent with the previous study and one is new. First, hue shift was peculiar to test chip hues. Although the results are not simple, the general tendency may be summarized as follows. The reduction of saturation or chroma of the test chips is explained by the decrease in output of the color opponent channels with decrease in illuminance level. If we assume that the reduction of the yellow/blue opponent channel output starts at an illuminance level higher than that of the red/green opponent channel output, the apparent hue should shift with illuminance levels. With decrease in illuminance at higher levels, color should shift toward a^* axis because of the reduction of yellow/blue signals. With decrease in illuminance at lower levels, color should shift toward the neutral point because of the reduction of both red/green and yellow/blue signals.

Second, the large changes of chroma and lightness occurred at the illuminance changes above 10 lx (presumably in the photopic level); this contrasts to smaller change below 10 lx (presumably in the mesopic level). These results suggest that color appearance changes with illuminance levels are most important at low levels of photopic vision.

Third, the new finding in this report, the distribution of the matching color at 0.01 lx was bimodal. There seem to be two categories of color appearance at the lowest illuminance level examined in the present study. The differences in rod and L-cone sensitivities to each test chip perhaps cause the difference in color appearance at a level. For the color chips with long wavelength reflection, we expect large activation of L-cones whereas we expect large activation of rods for color chips with short wavelength reflection. This difference would account for the difference in color appearance.

We built a model of color appearance in mesopic vision based on the present results in our second paper.[20] The model successfully predicted the results with an average error of 3 in the CIELAB $\Delta E_{ab}{}^*$, assuming the effects of illuminance change on the contributions of rods and cones to the luminance and opponent-color channels. The model analysis showed that there is a nonlinear relationship between illuminance level and rod and cone contributions to the opponent-color channels as well as to the luminance channels. To explain the results, the model assumes that cone contributions to the red/green and yellow/blue channels change differently with illuminance (faster reduction of contribution to the yellow/blue channel). An interesting result of the model is that major color change with illuminance can be explained by the reductions of cone contributions to the opponent-color channels. That is, only slight contribution of rods is necessary to explain the hue shift and the reduction of chromatic component. The rod contributions are necessary to explain the distribution of results at 0.01 lx while the hue shift and the reduction of chromatic component at higher illuminances can be predicted by changes in cone contribution.

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