Color Appearance in Mesopic Vision and its Modeling

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Abstract

Mesopic vision describes a range of light levels where vision is mediated by both cones and rods. The color appearance in mesopic vision differs drastically from that in photopic vision, where only cones mediate visual information.

We conducted a set of experiments to investigate the change of color appearance under various illuminance levels, ranging from photopic to scotopic via mesopic levels. In the experiments, we measured the corresponding color of color chips under various illuminance levels by a haploscopic color matching. The results showed that the hue of the most color chips changed with illuminance and the manor of the hue shift depended on color, while matching points of all chips approached the area around neutral gray with decrease of the illuminance level. The lightness of matched color decreased with decrease of the illuminance level, however, the lightness for bluish color chips did not decrease much in general and even increased in some cases, which is referred to as the Purkinje shift.

Base on these results, we propose a model of color appearance in mesopic vision.

Introduction

Vision may be classified simply into two: 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 the levels is called as mesopic vision. Color appearance in mesopic vision differs from that in photopic vision and is not easily estimated from the knowledge of photopic and scotopic vision. In order to predict color appearance in mesopic vision, it is necessary to understand and model interactions between cone and rod signals.

There are a number of studies in the literature on the evaluation of color appearance in mesopic vision. These studies[1-13] have revealed that there are interactions between cones and rods related to color vision. For example, Buck et al.[7-10] have shown the influence of rod signals on both red/green and blue/yellow opponent color channels. They also suggested schematic view of the color vision model at low light levels by summarizing results from their psychophysical experiments.

To predict mesopic color appearance, quantitative model based on quantitative data with wide range of stimulus colors are necessary. In this study, we evaluated the color appearance quantitatively under various illuminance levels, ranging from photopic to scotopic via mesopic levels in terms of color matching experiments. Careful evaluation of color appearance was made with a large number of color chips to build a model of mesopic color vision[13]. Our model is based on the opponent-color theory as are many of the models previous proposed.[14-16]

Methods

Apparatus and Stimuli

A haploscopic color matching technique was employed to match a reference color presented in the right eye to the test color presented in the left eye. The experimental booth with two rooms divided by a separation was set in a dark room (figure 1), where each eye was exposed to an illuminant condition controlled independently. Since we used different illuminant conditions between the test and reference stimuli, this was asymmetric matching. Inside wall including background of the stimulus was covered by gray paper whose lightness was equivalent to that of the Munsell N5 color chips. The test color chip was either one of 48 color chips previously chosen and they are used under six illuminance levels. The reference stimulus was generated on a CRT display under photopic level illumination. There were each 15 fluorescent lamps, which simulated D65, above each stimulus field. The illuminance of the reference fields was fixed at 1000 lx and the illuminance of the test field was either illuminance level of 1000, 100, 10, 1, 0.1, or 0.01 lx. Each illuminance level in the test field was adjusted to each desired level by the number of lighting lamps and ND filters.

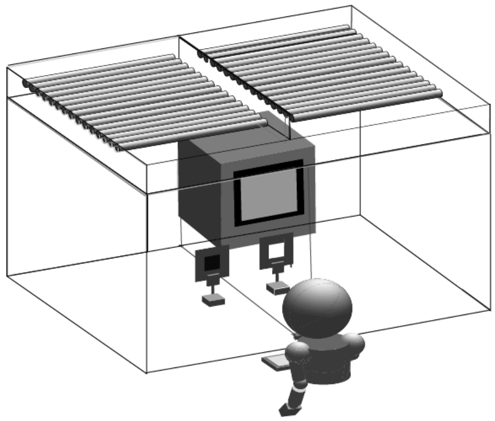

Figure 1. The experimental set up

The 48 color chips (JIS standard based on Munsell color system) included 45 chromatic color chips and three achromatic color chips with various values and chroma. Details are shown in Table 1. The reference color was generated on a 21'' CRT display (SONY Multiscan G500) controlled by a video board (VSG, visual stimulus generator by Cambridge System) with 15 bits intensity resolution for each phosphor. The CRT display had been calibrated by a spectroradiometer (MINOLTA CS-1000) before the experiment. The stimulus size was 10×10 deg. in both test and reference, where rods should be active.

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

Three males and two females with normal color vision participated in the matching experiments.

Procedure

Both eyes were dark adapted for 15 min. before high illuminance level conditions (1000, 100, 10 lx) and for 30 min. before low illuminance level conditions (1, 0.1, 0.01 lx). After the dark adaptation, eyes were adapted to each illuminance level for 5 min. in each condition. In a session, observers adjusted the chromaticity and the luminance of the reference color to appear the same in color as the test color chip. The adjustment was replicated three times for one color chip and the next test color chips. Observers adjusted the reference color for all color chips during a session.

Results and Discussions

We present the results averaged over repeated sessions and observers for selected test color chips to describe the primary feature of the results. General tendencies of the results described below are robust for single sessions and individual observers.

Hue and Chroma Changes

Figure 2 shows the change in color appearance of the test color chips with high chroma in the opponent-color space, which were calculated using Judd modified color matching functions. The most prominent feature of the results is that the matching points approach the neutral gray (the center of the dotted cross) with decrease in illuminance. The way of approaching differs with different chips. The matching points of reddish color chips (*L-2M* is plus at 1000 lx) at 0.01 lx compact together at a point slightly right of the neutral point whereas the points of greenish color chips (*L-2M* is minus at 1000 lx) compact at a point slightly left of the neutral point. This is consistent with the presumption that rods strengthen the blueness or give an influence on yellow/blue opponent color channels in the mesopic vision.

The decrease in saturation with decrease in illuminance is not isotropical among hue angles. If there were no color seen at 0.01 lx, the matching point should distribute around the neutral gray. The results disagree with this simple prediction. We suggest that color can be perceived even at 0.01 lx.

The following describe other details of hue changes among different color chips.

1) Y, YR, R color chips (No. 3, 6, 11):

After shifting toward horizontal axis (the direction in longer dominant wavelength) at the range between 1000 and 10 lx, the matching color approaches the neutral gray axis in the mesopic ranges (1~0.01 lx).

2) RP, P, PB color chips (No. 17, 19, 24):

After shifting toward vertical axis (the direction in shorter dominant wavelength) at the range between 1000 and 1 lx, the matching color approaches the neutral gray axis in the mesopic range (0.1~0.01 lx).

3) B, BG color chips (No. 25, 31, 35):

After shifting toward vertical axis (the direction in longer dominant wavelength) at the range between 1000 and 10 lx, the matching color approaches the neutral gray axis in the mesopic range (10~0.01 lx).

4) G, GY color chips (No. 39, 42, 45):

The hue angles of the matching points for these chips are relatively consistent through the whole illuminant range. The matching color approaches the gray point at 0.01 lx approximately directly.

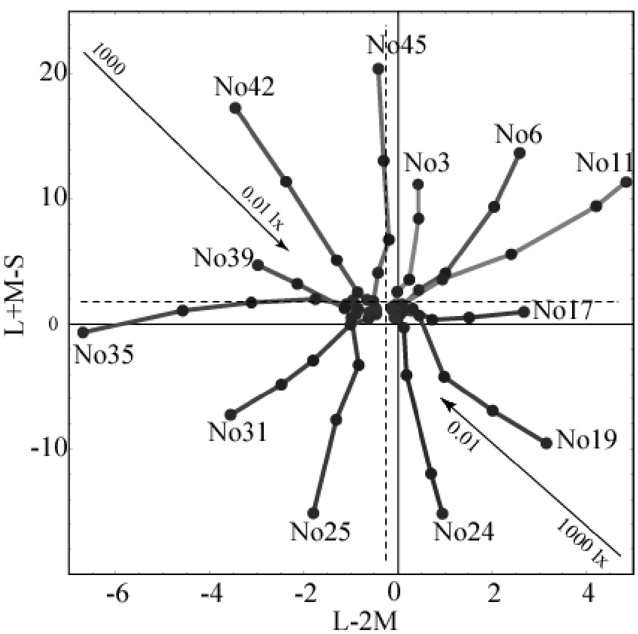

Figure 2. Change in hue appearance of each color chip (The center of dotted line means the coordinates of illuminanation)

Lightness Changes

Figure 3 shows the lightness changes of each color chip as a function of in illuminance level. We divided the data into two groups, dependently on whether the matched lightness increases or not with decrease of illuminance level in the mesopic range. The lightness for the reddish chips with reflectance of longer wavelength light monotonically decreases with decrease in illuminance level up to an illuminance level, beyond which lightness is about constant. The illuminance levels without lightness change differed between 10 and 0.01 lx dependently on color chips. The amount of lightness change differs according to lightness value at 1000 lx as well as hue and chroma. The lightness of the bluish chips shows a minimum value at around 10~1 lx after the decrease with iluminance level and then the lightness increases with further decrease in illuminance level. The increase is prominent in P, PB color chips as expected from Purkinje shift.

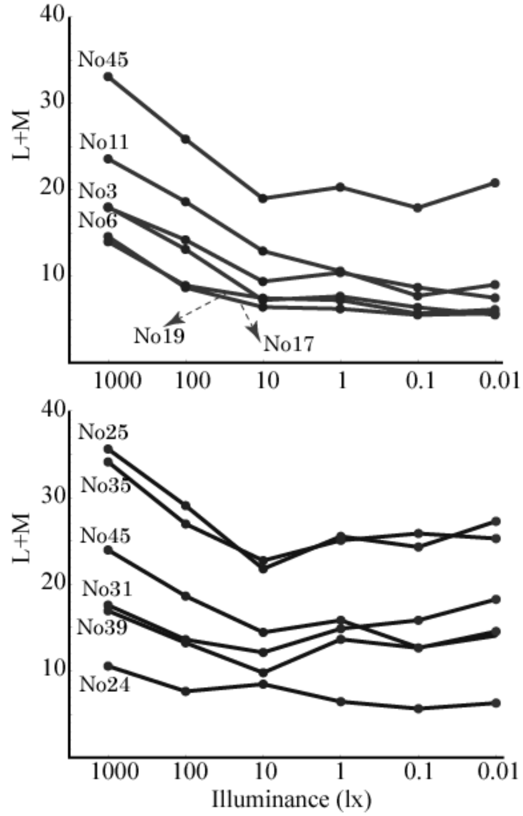

Figure 3. L+M change of each color chip at each illuminance level

Mesopic Color Appearance Model

Based on the results, we built a model to predict the color appearance in mesopic vision. The following features, we think, that the model has to have

1) The model should include gradual shift in spectral luminous efficiency changes from V (λ) to V' (λ) to cope with spectral sensitivity difference between photopic vision and scotopic vision.
2) The model should assume also the decrease of chromatic component with decrease in illuminance as the experimental results shows.
3) In order to explain hue shifts with illuminance, the model should assume that red/green and blue/yellow components change with illuminance levels independently.

We built a model based on the conventional opponent-color model. The model assumes one achromatic channel, called luminance channel, and two opponent-color channels, called red-green and blue-yellow opponent-color channels. To express rod intrusion to each channel, rod signals are added. The weights of the cone and rod signals vary dependently on illuminance levels. The weight of cone signal decreases with decrease in illuminance while the weight of rod signals increase in the model. The output of each channel is formulated in Equations (1), (2) or (3). For these equations, L, M, and S were calculated using Judd modified color matching functions that represent the cone fundamentals of Smith et al.[17]

$$rLum\,(E) = \alpha(E)100((L+M)p/(L+M)w) + \beta(E)78.4(Y'/Y'w)^{0.77} \quad (1)$$

$$r/g\,(E) = l(E)(L-2M)p + a(E)Y' \quad (2)$$

$$b/y\,(E) = m(E)(L+M-S)p + b(E)Y' \quad (3)$$

where, Lp, Mp and Sp represent cone outputs at 1000 lx, and $(L+M)\,p$, $(L-2M)\,p$, and $(L+M-S)\,p$ represent outputs of the luminance, red-green and blue-yellow channels at 1000 lx. Y' represents the scotopic luminance factor, which can be regarded as rod output. Weighting coefficients, $\alpha(E)$, $\beta(E)$, $l(E)$, $m(E)$, $a(E)$ and $b(E)$ are functions of illuminance, E. The values were determined to predict results best at each illuminance level and shown in figure 4.

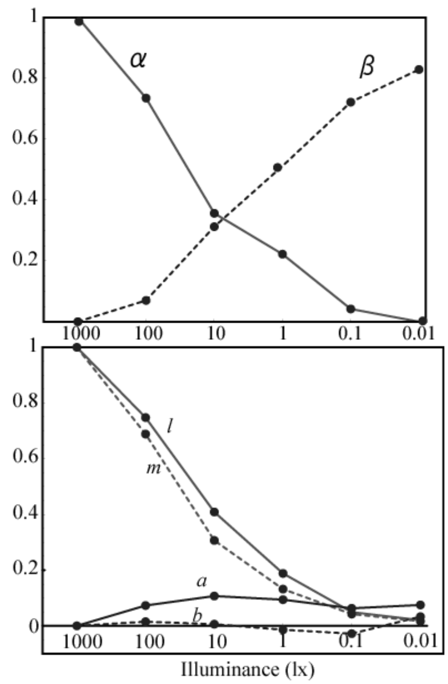

Figure 4. Weighting coefficient value for the model

$(L+M)w$ and $Y'w$ are outputs of photopic and scotopic luminance channels for white. These values normalize the luminance of reference color to obtain the lightness of the color. The exponent of $Y'/Y'w$ was to explain the nonlinear relationship between channels outputs of photopic and scotopic luminance, which is shown in figure 5. The value of 0.77 is for best least square fitting.

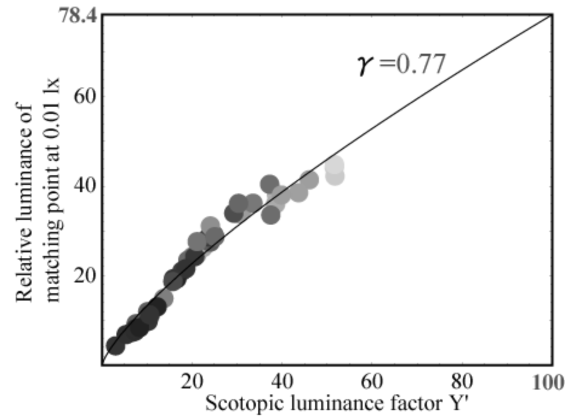

Figure 5. Relation between scotopic luminance factor Y' and relative luminance of matching point at 0.01 lx

The performance of the model was evaluated using the color differences ΔEab^* on the CIELAB, but calculated with the Judd modified color matching functions. The color differences between the predicted and the experimental values are showed in figure 6. The average color differences are about 3 with slightly smaller values in the mesopic ranges. These numbers is compatible to the color discrimination threshold. This indicates that the model is applicable in simulating colors in mesopic vision on practical image display systems.

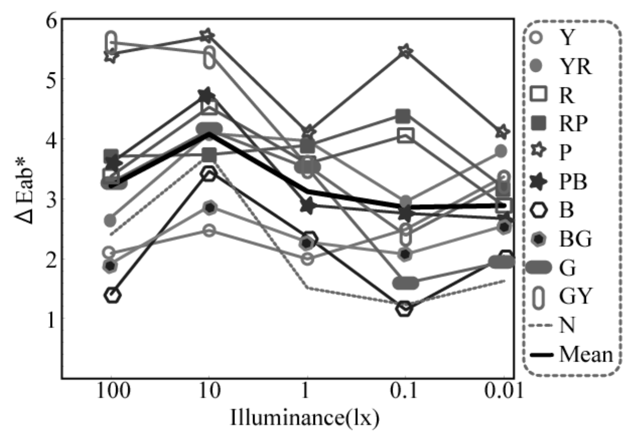

Figure 6. Color differences between predicted value and experimental value

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Biography

JaeChul Shin received his B.E. and M.E. degrees in imaging science from Chiba University, Japan in 1998 and 2000 respectively. He was a visiting pre-doctoral fellow of the Munsell Color Science Laboratory, RIT from 2000 to 2001. He is a Ph.D. candidate at the Chiba University. His research interests include color appearance and color reproduction based on human color vision mechanism.