Imaging system for mesopic vision

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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 carried out haploscopic color matches to investigate the color appearance under various illuminance levels, ranging from photopic to scotopic via mesopic levels. Using these experimental data, we developed a color appearance model applicable in mesopic vision. The model takes into account of rod intrusion both in the two color opponent channels and the luminance channel so that hue, saturation and lightness change with illuminance level. Finally, we propose an imaging system that provides color appearance of any natural scene under any illuminance level.

1. INTRODUCTION

Human visual system covers a wide range illuminance range from 10^5 lx to 10^{-3} lx. This wide dynamic range is achieved with two kinds of photoreceptors in the retina, rods and cones. There are illuminance levels where both rods and cones are active. The vision at these levels is called mesopic vision. Color appearance in mesopic vision differs from that in photopic or scotopic vision. Imaging systems on the market such as digital cameras and photographic films, however, are based on the human color vision in photopic vision. So, it is hard to reproduce image that would be seen in mesopic vision by the current imaging system. In order to predict a color appearance in mesopic vision, we have to consider the interaction between cone and rod at levels of mesopic vision.

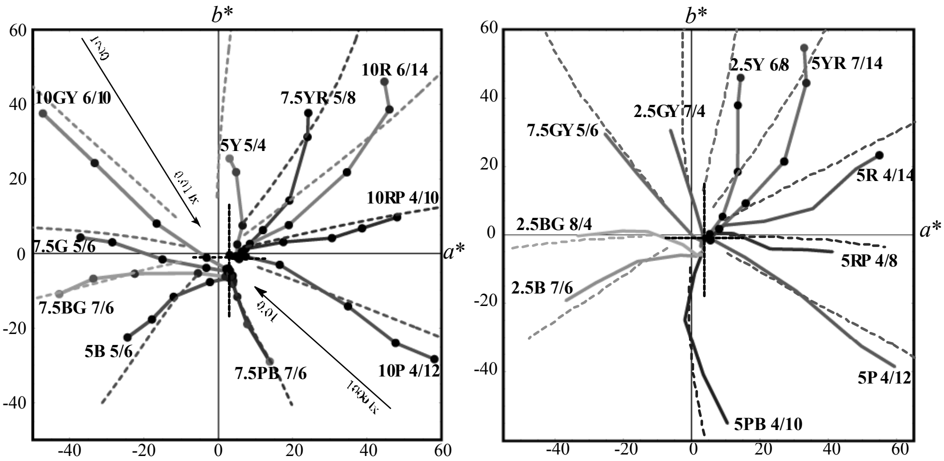
We carried out haploscopic color matches to investigate the color appearance under various illuminance levels, ranging from photopic to scotopic via mesopic levels. Using these experimental data, we developed a color appearance model applicable in mesopic vision. Finally, we propose an imaging system that provides color appearance of any natural scene under any illuminance level.

2. EXPERIMENTAL DATA OF MESOPIC COLOR APPEARANCE

There are a number of studies[1-6] on color appearance in mesopic vision. Among these experimental data, we employed our experimental data[6] to develop a color appearance model for mesopic vision.

In our experiment, a haploscopic color matching technique was employed to measure the corresponding color of test color chips under various illuminance levels. The observer saw a test color chip with his/her left eye and adjusted the appearance of the color presented on the CRT display with the right eye so as to match the appearance of the test color. The test color chip was presented in the left room of the booth under one of the illuminance levels of 1000, 100, 10, 1, 0.1, and 0.01 lx. The test stimulus was one of 48 color chips including 3 achromatic color chips. The matching stimulus was generated on a CRT display set behind the booth so that the observer saw the color through an aperture. The illuminance level of the matching field was fixed at 1000 lx. Three males and two females with normal color vision participated in the experiments.

Figure 1 (a), (b) show the color appearance of 20 test chips approximately equally spaced in hue angle in the CIELAB a^*-b^* diagram as a function of illuminance level. These plots are mean data for all observers. Chroma reduced continuously with decrease of the illuminance level until 0.01 lx. The loci of matching color on the a^*-b^* diagram were not straight for many test color chips, indicating that hue shift with the change in illuminance level.



(a) (b)

Figure 1(a), (b): Changes in color appearance of 20 test chips approximately equally spaced in hue angle in the CIELAB color space, (a) shows half and (b) shows the other half. Dashed lines indicate the loci of constant hue and chroma of the Munsell color system. The center of the dashed cross indicates the matching point of N5 under 1000 lx.

3. A MESOPIC COLOR APPEARANCE MODEL[7]

We applied the Boynton's two-stage color-vision model[8] to our mesopic color vision model. The model assumes that opponent-color process converts signals from L, M and S cones to red/green and yellow/blue opponent-color and luminance responses, that is, $L - 2M$, $L + M - S$ and $L + M$. Before the conversions, L, M and S stimulus values were derived using the Judd modified X, Y and Z tristimulus values with the Smith and Pokorny's transfer formula[9]. The presented model puts a rod intrusion in each of the opponent channels and rod signals and their amount varied depending on the illuminance levels and on the channels. The amount of the cone signals also varied depending on the illuminance levels and on the channels. The weight of cone signals decreases with decrease in illuminance while the weight of rod signals increase. The output of each channel is formulated in Eqs. (1), (2) and (3),

$$A(E) = \alpha(E) K_{\mathrm{w}} \frac{\left(L_{\mathrm{p}} + M_{\mathrm{p}}\right)}{\left(L_{\mathrm{p}} + M_{\mathrm{p}}\right)_{\mathrm{w}}} + \beta(E) K'_{\mathrm{w}} \left(\frac{Y'}{Y'_{\mathrm{w}}}\right)^{\gamma} \qquad (1)$$

$$r/g(E) = l(E)\left(L_{\mathrm{p}} - M_{\mathrm{p}}\right) + a(E)Y' \qquad (2)$$

$$y/b(E) = m(E)\left(L_{\mathrm{p}} + M_{\mathrm{p}} - S_{\mathrm{p}}\right) + b(E)Y' \qquad (3)$$

where L_{p}, M_{p} and S_{p} represent cone stimulus values at photopic condition, and $A(E)$, $r/g(E)$ and $y/b(E)$ represent outputs of the luminance, red/green and yellow/blue channels at illuminance level of E. Y' represents the scotopic luminance factor, which can be regarded as rod output. Y' is calculated for each test chip by the CIE spectral luminous efficiency $V'(\lambda)$. The weighting coefficients, $\alpha(E)$ and $\beta(E)$ indicate contribution amounts of photopic and scotopic luminance as a function of illuminance E. K_{w} and K'_{w} indicate the maximum response (the response to white) of the luminance channel at photopic and scotopic levels, and γ is the parameter to express the nonlinear relationship between photopic and scotopic luminance channels. The weighting coefficients, $l(E)$ and $a(E)$ indicate contribution amounts of the photopic red/green process (red/green signal made of L and M cone outputs) and rod to the red/green channel. The weighting coefficients, $m(E)$ and $b(E)$ indicate contribution amounts of the photopic yellow/blue process (yellow/blue signal made of L, M and S cone outputs) and rod to the yellow/blue channel. These weighting coefficients vary with illuminance level of E to express the change of contribution amounts of the factors among different illuminance levels as shown in Figure 2.

In order to estimate how accurately the model predicts the experimental results, we calculated the CIE color differences between the experimental data and model predictions obtaining L^*, a^* and b^* coordinates using the Judd modified color matching functions. The average ΔE^*_{ab} value is about 3 at the illuminance below 1 lx and about 4 at 10 lx. The error of the prediction is large for the purple region. The major error comes from the predictions of Δb^*. The Δb^* is the largest among ΔL^*, Δa^* and Δb^*, 2.01, 2.91 and 3.75, respectively, for the illuminance of 10 lx.

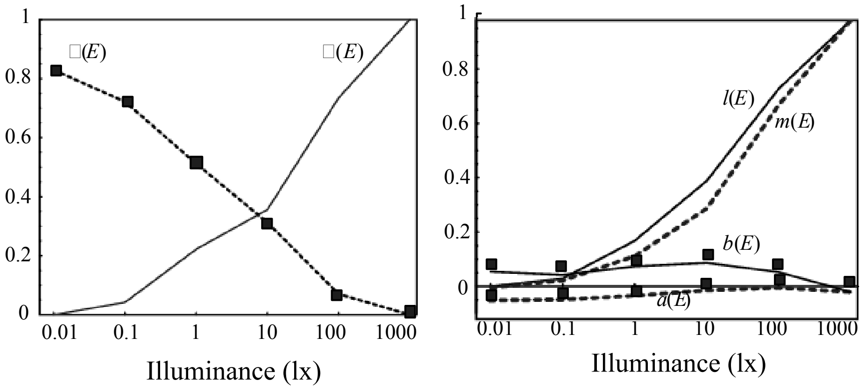


Figure 2: Weighting coefficients of the model as a function of illuminance.

4. AN IMAGING SYSTEM FOR MESOPIC COLOR APPEARANCE

Figure 3 shows a flow chart of the imaging. At first, the scene of interest is taken by a digital camera, and get data of R_{camera}, G_{camera} and B_{camera} for each pixel. Secondly, the pixel data are transformed to the X, Y, Z tristimulus values and the scotopic luminance factor, Y' using the camera model, where the secondary polynomial function of R, G, B are used to obtain X, Y, Z and Y'. Thirdly, the X, Y, Z tristimulus values are converted to the cone stimulus values at a photopic level (L_p, M_p, S_p). Then, in order to obtain output values of the opponent state at a given illuminance E, L_p, M_p, and S_p are input to the mesopic color appearance model with the weighting coefficients which depend on illuminance E. From the tristimulus values, the model provides outputs of the opponent channel ($Lum(E)$, $r/g(E)$ and $y/b(E)$) at the illuminance E, which in turn are transformed to tristimulus values. Finally, using the output device colorimetric model, X, Y, Z tristimulus values are transformed to R_{output}, G_{output} and B_{output} digital unit for each pixel of the scene.

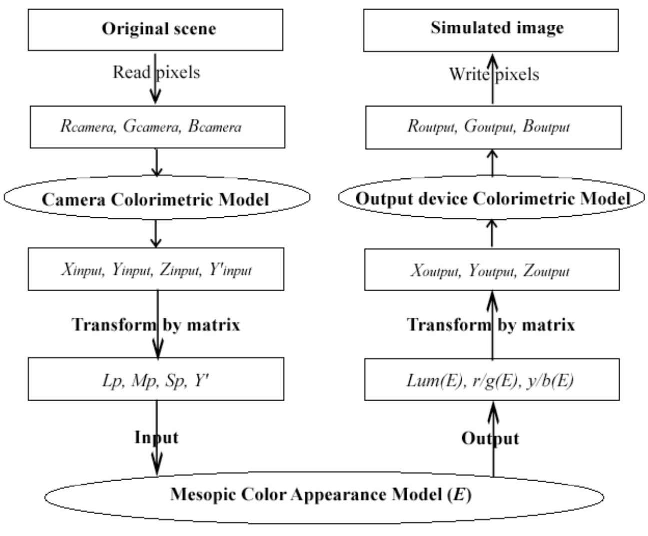


Figure 3: Flowchart of an imaging system for mesopic vision.

Figure 4 shows a set of the example scenes which would be seen under six different illuminance, 1,000, 100, 10, 1, 0,1 and 0.01 lx. The imaging system proposed in the present paper would be very useful for many industrial fields such as designing traffic environment, making a movie picture of night scene and so on.

Figure 4: A set of example scenes which would be seen under various illuminance, from top left to bottom right: 1,000, 100, 10, 1, 0.1, 0.01 lx.

5. CONCLUSIONS

We propose an imaging system based on the mesopic color appearance model. The model has rod signals in the luminance channel as well as the two opponent-color channels. The imaging system consisting of a conventional digital camera and a CRT display can successfully reproduce color image that would be seen in any illuminance level including mesopic environment.

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