Prediction of color reproduction for skin color under different illuminants based on the color appearance models

Francisco Hideki Imai, Norimichi Tsumura,
Hideaki Haneishi, and Yoichi Miyake

Department of Information and Computer Sciences, Chiba University
1-33 Yayoi-cho, Inage-ku, Chiba-shi, Chiba-ken 263
JAPAN

Tel & Fax: +81-43-290-3262
e-mail: imai@icsd6.tj.chiba-u.ac.jp

Abstract

In this paper, we study a color reproduction method to match the appearance of skin color images on CRT with a hardcopy under various viewing illuminants. Three color appearance models, von Kries, Fairchild and CIELAB, were applied to predict color reproduction on CRT display. Optimum color appearance model to predict color reproduction was estimated by psychophysical experiments based on the memory matching. As the result of the experiment, differences in visual perception between skin color patches and facial pattern images are also described.

Introduction

In the development of cosmetics and their sales promotion, it is required to predict skin color images under various illuminants, because appearance of skin color is depending on the illuminant in the environment. In our previous paper,[1] we proposed a colorimetric method to predict skin color images under various illuminants on a CRT and a hardcopy. In the paper, the spectral reflectance was estimated based on the principal component analysis, and the estimated spectral reflectance of human skin was used for the computer simulation of the colorimetric color reproduction.

One of the most significant factors affecting color appearance is the change of visual color sensitivities corresponding to changes of the illumination. This phenomenon is known as chromatic adaptation. There are two types of chromatic adaptation mechanisms: sensory and cognitive.[2] Sensory mechanisms respond automatically to the stimulus and are based on the sensitivity control in the photoreceptors and neurons in the first stages of the visual system. The first model of sensory chromatic adaptation was proposed by von Kries.[3] Subsequent models of chromatic adaptation by Hunt[4], Nayatani *et al*.,[5] and Fairchild[6,7], and color spaces such as CIELAB[8], RLAB[2] are all extensions of the von Kries model. Such color appearance models consider changes in the white point, luminance, and other aspects of the viewing conditions. On the other hand, cognitive mechanisms are influenced by observers' knowledge of image content. It is impossible to quantify directly the effect produced by such mechanisms.

The color appearance models have been applied to cross-media reproduction. In the field of color imaging, many works have been published concerning the color reproduction between CRT display and hardcopy.[9,10,11,12] These works are concerned in cross-media reproduction, however they are not considering the reproduction of an original scene under various illuminants on a CRT display.

In this paper, we study a color reproduction system to predict the appearance of skin color image under various viewing illuminants. The color appearance model is applied to the colorimetric color reproduction method[1]. Then, on a CRT display, we can achieve corresponding color reproduction[13] of printed skin color images under different viewing illuminants. Optimum color appearance model to predict color reproduction is estimated by psychophysical experiments based on the memory matching. One advantage of the system used in this study is the possibility to reproduce images on CRT that match the color appearance with the original scene under various illuminants.

In the following sections, we present overview of the von Kries, Fairchild and CIELAB color appearance models, and an outline of previously proposed colorimetric color reproduction method for skin color image. After these overviews and an outline, we present a description of the proposed method, the psychophysical experiments and its results. Finally, we will discuss the difference in visual perception between skin color patches and facial pattern images.

Color Appearance Models Overview

The calculation of color appearance is processed using the cone fundamental tristimulus values *L, M, S.* Then, the first step is a transformation from tristimulus values, *X, Y, Z* to cone fundamental tristimulus values *L, M,* and *S*. The Hunt-Pointer-Estévez transformation normalized to CIE Illuminant D65 is used to calculate *L, M, S* values, as shown in Eqs. 1 and 2.[2]

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \boldsymbol{M} \begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} \qquad (1)$$

$$\boldsymbol{M} = \begin{bmatrix} 0.40 & 0.71 & -0.08 \\ -0.23 & 1.17 & 0.05 \\ 0.0 & 0.0 & 0.92 \end{bmatrix} \qquad (2)$$

von Kries model

The von Kries model considers that human color visual system adapts completely to the white point of the illuminant. In the von Kries model[3] the cone fundamental tristimulus values *L, M, S* are simply multiplicated by constant values, respectively. The constant values are taken to be the inverses of the respective cone responses for the maximum signal of the illuminant. Then, the responses after the adaptation, L_a, M_a, and S_a can be written as follows:

$$L_a = k_L L, \quad k_L = \frac{L_{Na}}{L_{Noriginal}}, \tag{3a}$$

$$M_a = k_M M, \quad k_M = \frac{M_{Na}}{M_{Noriginal}}, \tag{3b}$$

$$S_a = k_S S, \quad k_S = \frac{S_{Na}}{S_{Noriginal}}, \tag{3c}$$

where, *L, M,* and *S* are the excitations of cones on retina before the adaptation, k_L, k_M, and k_S are multiplicative factors, L_{Na}, M_{Na}, and S_{Na} are cone excitations for the white point after adaptation, and $L_{Noriginal}$, $M_{Noriginal}$, and $S_{Noriginal}$ are the cone excitations for the white point of original illuminant.

Fairchild incomplete adaptation model

The Fairchild color appearance model[6,7] considers incomplete chromatic adaptation of cones to the white point. Fairchild modified von Kries model based on a functional expression proposed by Hunt[4] for incomplete levels of adaptation as shown in Eq. 4.

$$L' = \rho_L L/L_N \tag{4a}$$

$$M' = \rho_M M/M_N ,\qquad (4b)$$
$$S' = \rho_S S/S_N \qquad (4c)$$

where *L', M',* and *S'* are the cone excitations considering a certain degree of chromatic adaptation, ρ_L, ρ_M, and ρ_S are parameters to represent degree of chromatic adaptation of cones, respectively. L_N, M_N, S_N are respectively the *L, M, S* cone responses to the white point of the illuminant. Equation 4 can be expressed in matrix form as shown in Eq. 5.

$$\begin{bmatrix} L' \\ M' \\ S' \end{bmatrix} = A \begin{bmatrix} L \\ M \\ S \end{bmatrix}, \qquad (5)$$

The matrix *A* is

$$\begin{bmatrix} a_L & 0 & 0 \\ 0 & a_M & 0 \\ 0 & 0 & a_s \end{bmatrix}, \qquad (6)$$

where $a_L = \rho_L/L_N$, (7a)

$$a_M = \rho_M/M_N , \qquad (7b)$$
$$a_S = \rho_S/S_N . \qquad (7c)$$

The degree of chromatic adaptation can be calculated as follows:

$$\rho_L = \frac{\left(1 + Y_N^{\upsilon} + l_E\right)}{\left(1 + Y_N^{\upsilon} + 1/l_E\right)} \qquad (8a)$$

$$\rho_M = \frac{\left(1 + Y_N^{\upsilon} + m_E\right)}{\left(1 + Y_N^{\upsilon} + 1/m_E\right)}, \qquad (8b)$$

$$\rho_S = \frac{\left(1 + Y_N^{\upsilon} + s_E\right)}{\left(1 + Y_N^{\upsilon} + 1/s_E\right)} \qquad (8c)$$

where Y_N is the luminance of the illuminant, υ is an exponent that defines the shape of the degree of the adaptation function and l_E, m_E, and s_E are the fundamental chromaticity coordinates of the adapting stimulus. Hunt[4] suggested a value of 1/4.5 for the exponent υ in a dark environment. The l_E, m_E, and s_E values can be calculated as follows:

$$l_E = \frac{3L_N}{L_N + M_N + S_N}, \qquad (9a)$$

$$m_E = \frac{3M_N}{L_N + M_N + S_N}, \qquad (9b)$$

$$s_E = \frac{3S_N}{L_N + M_N + S_N}. \qquad (9c)$$

From the Eqs. 4 to 9 we can see that adaptation will be less complete as the saturation of the adapting stimulus increases, and more complete as the luminance of the adapting stimulus increases.

The final step in the calculation of post adaptation signals is a transformation for luminance-dependent interaction among the three cone types given by Eq. (5). This transformation allows the model to predict increases of the perceived colorfulness and contrast with increasing luminance, the Hunt effect, and the Stevens effect, respectively.

$$\begin{bmatrix} L_a \\ M_a \\ S_a \end{bmatrix} = \begin{bmatrix} 1 & c & c \\ c & 1 & c \\ c & c & 1 \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix}, \qquad (10)$$

where c is calculated as follows:

$$c = 0.2190 - 0.0784 \log_{10}(Y_N). \tag{11}$$

The entire model to predict the tristimulus values X_A, Y_A, Z_A in a second adapting condition from the tristimulus values *X, Y, Z* in a first adapting condition can be expressed by a single matrix equation as follows,

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = M^{-1} A_2^{-1} C_2^{-1} C_1 A_1 M \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \tag{12}$$

where matrix *M* is the transformation from tristimulus values to cone fundamental primaries presented in Eq. 2. Matrix A_1 and C_1 are respectively the matrices of Eqs. 6 and 10 for adapting condition 1. Matrix A_2 and C_2 are respectively the matrices of Eqs. 6 and 10 for adapting condition 2.

CIELAB

In 1976, CIE (Commission Internationale de l'Eclairage) recommended CIELAB color space[8] for color-difference metric which also incorporates a modified form of the von Kries model, X/X_N, Y/Y_N, and Z/Z_N as shown in Eq. 13;

$$L^* = 116\left(\frac{Y}{Y_N}\right)^{1/3} - 16, \tag{13a}$$

$$a^* = 500\left[\left(\frac{X}{X_N}\right)^{1/3} - \left(\frac{Y}{Y_N}\right)^{1/3}\right], \tag{13b}$$

$$b^* = 200\left[\left(\frac{Y}{Y_N}\right)^{1/3} - \left(\frac{Z}{Z_N}\right)^{1/3}\right], \tag{13c}$$

where *X, Y,* and *Z* are the tristimulus values, X_N, Y_N, and Z_N are the tristimulus values of the white point of the illumination, and L^*, a^*, and b^* are color metric defined by CIELAB 1976.

The tristimulus values X_a, Y_a, Z_a , after the chromatic adaptation can be calculated as follows:

$$X_a = \left(\frac{a^*}{500} + \left(\frac{L^* + 16}{116} \right) \right)^3 X'_N, \quad \text{(14a)}$$

$$Y_a = \left(\frac{L^* + 16}{116} \right) Y'_N, \quad \text{(14b)}$$

$$Z_a = \left(\left(\frac{L^* + 16}{116} \right) - \frac{b^*}{200} \right)^3 Z'_N, \quad \text{(14c)}$$

where L^*, a^*, and b^* are values calculated by Eqs. 13 and X'_N, Y'_N, and Z'_N are the tristimulus values of the white point of the adapting illuminant. It is possible to see in Eqs. 13 and 14 that CIELAB normalizes the tristimulus values of the stimulus by values of a stimulus defined to be the illuminant tristimulus values. The CIELAB color space can be used as a first approximation to a color appearance space.[2]

Colorimetric Color Reproduction of Skin Color: Outline

For colorimetric color reproduction of skin color, we had proposed a method to predict the tristimulus values of skin color image under various illuminants[1], as shown in the schematic diagram of Fig. 1. A skin color image taken by HDTV camera was transformed from the original *RGB* data to *X, Y,* and *Z* tristimulus values by matrix $\boldsymbol{M}_1$ obtained by multiple regression analysis of skin color patches. To calibrate HDTV camera, we used 39 skin color patches of Japanese women whose Munsell values are H=0YR-10YR, V=5-8, and C=2-5. We measured the tristimulus values of the skin color patches using a spectral colorimeter (Minolta CM-1000) and calculated the color transform matrix $\boldsymbol{M}_1$ by multiple regression analysis using the measured data and skin color patches R, G, B values digitized by the HDTV camera. Two dimensional distribution of spectral reflectance of skin $O(\lambda)$ was calculated from *X, Y,* and *Z* tristimulus values using the three principal components of spectral reflectance. The tristimulus values *X', Y',* and *Z'* of the image under various illuminants were predicted from both the spectral radiance distribution $E(\lambda)$ of each viewing illuminant and the estimated two dimensional spectral reflectance $O(\lambda)$. The spectral radiance distribution $E(\lambda)$ of each illuminant reflected on a white perfect diffuser was measured using a spectraradiometer (Abbe Sekkei Model 2706). The predicted tristimulus values are displayed on CRT in a dark environment and printed by color transform matrix for calibration. The white point of the CRT display was D65, and the luminance level was 93.34 cd/m^2. The luminance level was measured by a luminance colorimeter (Topcom BM-7) set at a distance of 50 cm from the center of monitor where the images were displayed in a dark environment.

The images displayed on CRT display were printed by a laser thermal exposure photographic transcription printer (Fujix Pictrography 3000) on Fujix Matte paper PG-SM. For printing, we used a color transform matrix obtained by multiple regression analysis based on a data base of the measured spectral reflectances of 108 skin patches. The accuracy of this colorimetric color reproduction was evaluated by averaged color differences of fifty five skin color patches used in the multiple regression analysis.

Color difference in CIEL*a*b* was calculated between CRT and hardcopy, with and without color transformation. The averaged color difference was 4.9. Six original skin color patches were viewed in the standard illumination booth with their colorimetric hardcopy under 4 illuminants ("A" , "Horizon", "DayLight" and "Cool White"). We measured the tristimulus values of the original patches and the reproductions under each illuminant using a luminance colorimeter (Topcom BM-7). The averaged color difference in LAB color space was 5.5. We could match visually the skin color and its reproduction under the same viewing condition. Then, the skin color image is reproduced colorimetrically both on CRT display and hardcopy. Here, it is noted that the color appearance on CRT display is different from the color appearance on hardcopy under various viewing illuminants because of the color adaptation, as mentioned before.

Corresponding color reproduction of skin color

Figure 2 shows a schematic diagram of the proposed corresponding color reproduction method for skin color. By using color appearance models, the tristimulus values X_a, Y_a, and Z_a after the chromatic adaptation can be calculated from the tristimulus values X', Y', and Z' obtained by colorimetric color reproduction. The first step is a transformation from tristimulus values, X', Y', and Z' to cone fundamental tristimulus values *L, M,* and *S* using Eqs. 1 and 2. Thereafter, the calculated *L, M,* and *S* values are used to estimate fundamental tristimulus values L_a, M_a, and S_a corresponding to the cone responses after the chromatic adaptation by using color appearance models. The values L_a, M_a, and S_a were predicted by using von Kries, and Fairchild models. We also used CIELAB coordinates to calculate the color appearance. Next, the tristimulus values X_a, Y_a, and Z_a considering chromatic adaptation are calculated by the inverse matrix of $\boldsymbol{M}_2$. Finally, the predicted image X_a, Y_a, and Z_a is reproduced on CRT display by color transform matrix.

Psychophysical experiment to select an optimum color appearance model for the proposed method

Optimum color appearance model to predict color reproduction was estimated by psychophysical experiments. The images on CRT display surrounded by a dark environment were compared with a hardcopy illuminated in the standard illumination booth (Macbeth Spectralight II). The white frame of the CRT display was covered by a black material to avoid any adaptation to the frame. The booth has four illuminants; “Day light” (6047 K), “A” (2,837 K), “Cool white” (3,957 K), and “Horizon” (2,320 K). The spectral radiances of the illuminants were measured by a spectroradiometer (Abbe Sekkei Model 2706). The chromaticities of the illuminants were measured using a luminance colorimeter (Topcom BM-7). The spectral radiances and chromaticities of the illuminants are shown in Fig. 3. Five facial pattern images with 1920 by 1035 pixels were taken by a HDTV camera under illuminant C.[14] The model is a Japanese young woman. Six skin color patches with same color in facial pattern are also prepared. The predicted color reproduction for skin color patches and facial pattern images in the viewing booth were displayed on CRT. The tristimulus values of the six color patches under “A” illuminant are shown in Table 1. Four images, XYZ, von Kries, Fairchild, CIELAB images are calculated for each viewing illuminant. The XYZ image is calculated from the tristimulus values, *X’, Y’* and *Z’* without considering chromatic adaptation. The images predicted colorimetrically for each illuminant were printed in the same way as explained in the outline of colorimetric color reproduction of skin color. A white background was used for both the hardcopy and the image on CRT display.

Figure 4 shows an example of predicted color based on color appearance models for the skin color patches under various illuminants. Figure 5 shows an example of predicted facial pattern images for each color appearance model under illuminant “A.” The images of Figs. 4 and 5 are predictions to be viewed on the CRT display in a dark environment. Therefore, the color process to print the images can change the appearance of skin colors.

A memory matching viewing technique, recommended by Braun and Fairchild,[15] was used to select an optimum color appearance model for skin color displayed on a CRT. As shown in Fig. 6, the CRT display and the standard illumination booth were angularly positioned at 90^{o} such that the observers can only see one of them at a time[16]. Both CRT display and hardcopy were arranged at the same viewing distance of approximately 50 cm from the observer. The images, whether it is on the CRT display or in the illumination booth, would be observed with both eyes. The observers are asked to look at the skin color print in the booth for about a minute, as long as necessary to stabilize the perception of the color. Then the observers compare the memorized color appearance of hardcopy with the four predicted XYZ, von Kries, Fairchild and CIELAB images displayed on CRT simultaneously. The position of each model on the CRT display was randomized for each set of predicted images. The observers were instructed to choose which of the four images was the best reproduction of the hardcopy. The observers can see the monitor and the hardcopy only once. Ten color-normal observers took part in this experiment. The observers were asked to read the following instructions before the experiment;

"In this experiment, you must compare a color image in the standard illumination booth with four reproductions displayed on CRT simultaneously. At first, you will look at the printed skin color image in the illuminant booth after adapting for about a minute. You will be asked to memorize the skin color of the image. Turn towards the CRT display, and look at the displayed neutral gray field. After adapting to the neutral gray field for a minute, examine the four reproductions and select the one that looks most like the hardcopy that you memorized. You must choose the reproduction on CRT based only on color judgment. You must judge only considering if the reproduction looks like the original hardcopy and not in the image quality or preference."

The psychophysical experiment was performed for both skin color images and facial pattern images.

Experimental Results and Discussion

Figure 7(a) shows the percentage of trials on which each reproduced skin color patch under various illuminants was chosen as the best one on CRT display. From Fig. 7(a), we can see that the color appearance of patch by Fairchild model was selected well as the best one. As a result, in an average of 71% of the trials the observers choose Fairchild model as best. Figure 7(b) shows the percentage of trials on which the reproduced image of six skin color patches for each illuminant was chosen as the best one on CRT display. We can see that the incomplete adaptation, Fairchild model, was effective under "Cool White", "Horizon", and Illuminant "A". However, under "Day Light" the Fairchild model was not as effective as other illuminants, because under this illuminant there is no significant degree of adaptation, producing imperceptible differences between the images predicted by von Kries and Fairchild.

On the other hand, Figure 8(a) shows the percentage of trials on which each reproduced facial pattern image under various illuminants was chosen. Fairchild model was selected well as the best one. As a result, in an average of 43% of the trials the observers choose Fairchild model as the best one. Figure 8(b) shows the percentage of trials on which the reproduction of five facial pattern images for each illuminant was chosen. In the case of facial pattern, there is no significant difference of experimental results among illuminants for each model.

Comparing Fig. 7 and Fig. 8, we can also find that there is a difference of the result about the percentage on the Fairchild model between the color patches and facial pattern. In the case of facial pattern, other color appearance models are selected more times than the color patches. It is known that the facial skin color is one of the human memorized colors. We guess that the difference of the result is due to the memorization. The color appearance of facial skin will be highly depending on the individual memorization.

We can conclude that the Fairchild model could be used in our proposing method for prediction of skin color patches, however it is not an optimum model for facial pattern images.

Conclusion

On the basis of appearance models, a corresponding color reproduction method was studied for skin color images under various illuminants. In our color reproduction system, the incomplete chromatic adaptation model proposed by Fairchild was significant for a suitable prediction of color appearance in skin color patches, however, there was not found an optimum color appearance model to predict color reproduction of facial pattern images. The results of the experiments showed that there is a difference between the perception of skin color patches and facial pattern images. The results of psychophysical experiments showed that more studies are necessary to consider the influence of memorized facial skin color in the cognitive mechanisms of chromatic adaptation. In future studies, experiments can be made to predict the color appearance of skin in various cross-media reproduction systems based on color appearance models.

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