Prediction of Color Reproduction for Skin Color Under Different Illuminants Based on Color Appearance Models

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

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Introduction

Development of cosmetics and their sales promotion requires prediction of skin color images under various illuminants, because appearance of skin color depends on the illuminant in the environment. In our previous article,[1] we proposed a colorimetric method to predict skin color images under various illuminants on a CRT and a hardcopy. In this report, the spectral reflectance was estimated based on principal component analysis, and the estimated spectral reflectance of human skin was used for computer simulation of colorimetric color reproduction.

One of the most significant factors affecting color appearance is the change of visual color sensitivities corresponding to changes of illumination. This phenomenon is known as chromatic adaptation. The two types of chromatic adaptation mechanisms are: sensory and cognitive.[2] Sensory mechanisms respond automatically to 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] Takahama, Sobagaki, and Nayatani,[5] and Fairchild,[6,7] and color spaces such as CIELAB,[8] and 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. Cognitive mechanisms also 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 color reproduction between a CRT display and hardcopy.[9–12] However, these works are concerned only with cross-media reproduction, not with the reproduction of an original scene under various illuminants on a CRT display.

In this article, 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 reproductions[13] of printed skin color images under different viewing illuminants. The optimum color appearance model to predict color reproduction is estimated by psychophysical experiments based on memory matching. One advantage of the system used in this study is the possibility to reproduce images on a CRT that match the color appearance with the original scene under various illuminants.

In the following sections, we present an overview of the von Kries, Fairchild, and CIELAB color appearance models and an outline of a previously proposed colorimetric color reproduction method for skin color images. Then, we present a description of the proposed method, the psychophysical experiments, and 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, and S. Then, the first step is a transformation from tristimulus values, X, Y, and 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, and S values, as shown[2] in Eqs. 1 and 2.

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

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

von Kries Model. This model considers that the 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, and S are simply multiplicated by constant values. The constant values are the inverses of the respective cone responses for the maximum signal of

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the illuminant. Then, the responses after the adaptation, L_a, M_a, and S_a can be written as follows:

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

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

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

where L, M, and S are the excitations of cones on the 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_{Norig}, M_{Norig}, and S_{Norig} are the cone excitations for the white point of the original illuminant.

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

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

$$M' = \rho_M M/M_N, \tag{4b}$$

$$S' = \rho_S S/S_N, \tag{4c}$$

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, and S_N are, respectively, the L, M, and S cone responses to the white point of the illuminant. Equation 4 can be expressed in matrix form as shown in Eq. 5.

$$\begin{bmatrix} L' \\ M' \\ S' \end{bmatrix} = \boldsymbol{A} \begin{bmatrix} L \\ M \\ S \end{bmatrix}, \tag{5}$$

The matrix **A** is

$$\begin{bmatrix} a_L & 0 & 0 \\ 0 & a_M & 0 \\ 0 & 0 & a_S \end{bmatrix}, \tag{6}$$

where

$$a_L = \rho_L/L_N, \tag{7a}$$

$$a_M = \rho_M/M_N, \tag{7b}$$

$$a_S = \rho_S/S_N. \tag{7c}$$

The degree of chromatic adaptation can be calculated as follows:

$$\rho_L = \frac{\left(1 + Y_N^v + l_E\right)}{\left(1 + Y_N^v + 1/l_E\right)}, \tag{8a}$$

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

$$\rho_S = \frac{\left(1 + Y_N^v + s_E\right)}{\left(1 + Y_N^v + 1/s_E\right)}, \tag{8c}$$

where Y_N is the luminance of the illuminant, v 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 v in a dark environment. The l_E, m_E, and s_E values can be calculated as follows:

$$l_E = \frac{3L_N}{L_N + M_N + S_N}, \tag{9a}$$

$$m_E = \frac{3M_N}{L_N + M_N + S_N}, \tag{9b}$$

$$s_E = \frac{3S_N}{L_N + M_N + S_N}, \tag{9c}$$

From 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 perceived colorfulness and contrast with increasing luminance, the Hunt effect, and the Stevens effect, respectively.

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

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, and Z_A in a second adapting condition from the tristimulus values X, Y, and Z in a first adapting condition can be expressed by a single matrix equation as follows,

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = \boldsymbol{M}^{-1}\boldsymbol{A}_2^{-1}\boldsymbol{C}_2^{-1}\boldsymbol{C}_1\boldsymbol{A}_1\boldsymbol{M} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \tag{12}$$

where matrix $\boldsymbol{M}$ is the transformation from tristimulus values to cone fundamental primaries presented in Eq. 2.

Matrices $\boldsymbol{A}_1$ and $\boldsymbol{C}_1$ are, respectively, the matrices of Eqs. 6 and 10 for adapting condition 1. Matrices $\boldsymbol{A}_2$ and $\boldsymbol{C}_2$ 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] as a color-difference metric that also incorporates a modified form of the von Kries model, $\boldsymbol{X}/X_N$, $\boldsymbol{Y}/Y_N$, and $\boldsymbol{Z}/Z_N$ as shown in Eq. 13;

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

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

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

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 the color metric defined by CIELAB 1976.

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

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

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

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

where L^*, a^*, and b^* are values calculated by Eqs. 13a, 13b, and 13c; and are the tristimulus values of the white point of the adapting illuminant. Note 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 previously proposed a method to predict tristimulus values of skin color images 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 analyses of skin color patches. To calibrate the HDTV camera, we used 39 skin color patches of Japanese women whose Munsell values are H = 0 to 10 YR, V = 5 to 8, and C = 2 to 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, and 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 spectroradiometer (Abbe Sekkei Model 2706). The predicted tristimulus values are displayed on a CRT in a dark environment and printed by a color transform matrix for calibration. The white point of the CRT display was D65, and the luminance level was 93.34 cd/m². The luminance level was measured by a luminance colorimeter (Topcom BM-7) set at a distance of 50 cm from the center of the monitor where the images were displayed in a dark environment.

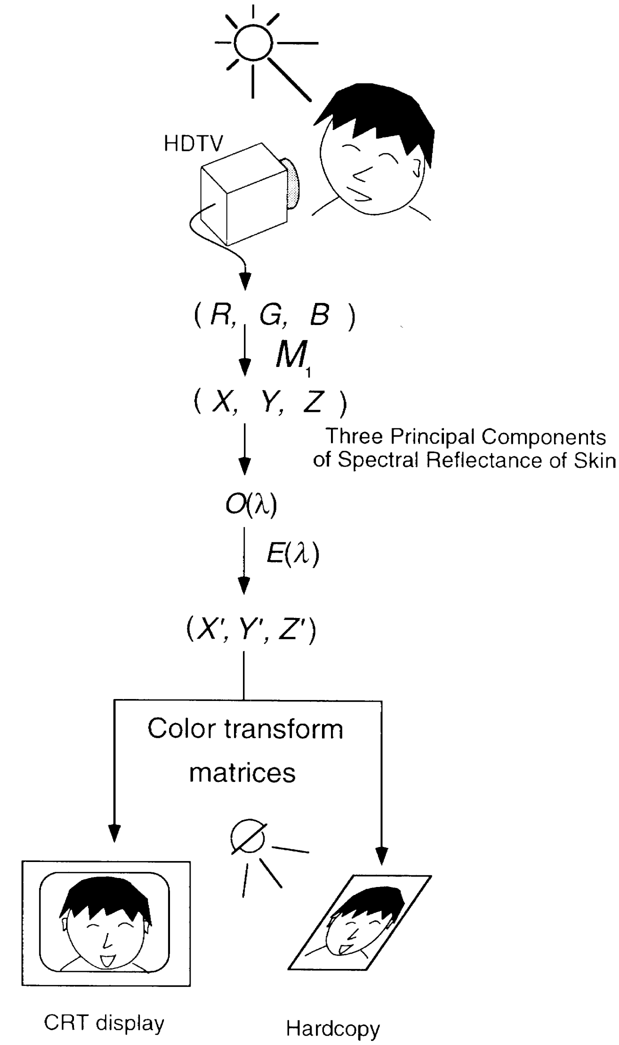


Figure 1. Diagram of colorimetric prediction of skin color image under various illuminants.

The images displayed on the CRT display were printed by a laser thermal exposure photographic transcription printer (Fujix Petrography 3000) on Fujix Matte paper PG-SM. For printing, we used a color transform matrix obtained by multiple regression analysis based on a database of the measured spectral reflectances of 108 skin patches. The accuracy of this colorimetric color reproduction was evaluated by averaged color differences of 55 skin color patches used in the multiple regression analysis.

Color difference in CIEL*a*b* was calculated between a 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 four 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

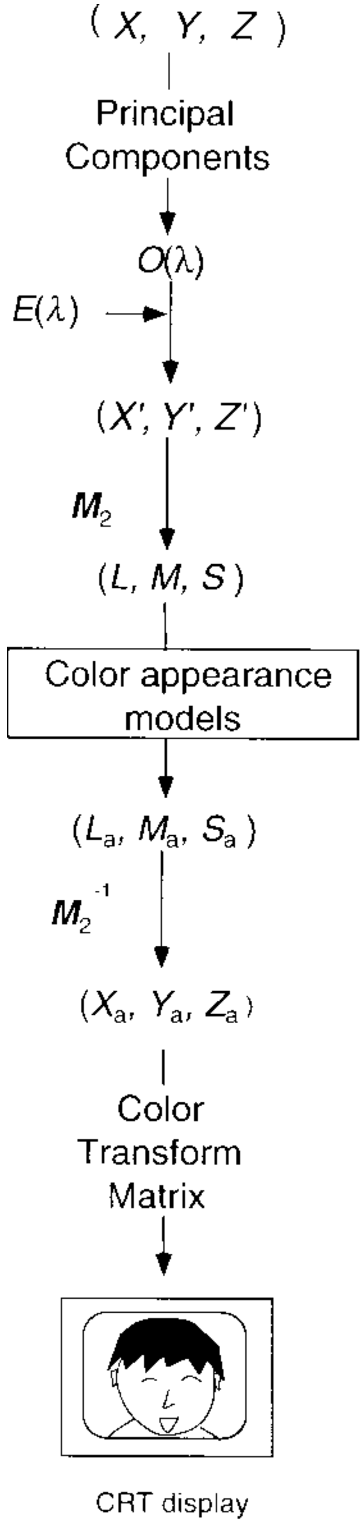


Figure 2. Diagram of corresponding color reproduction method of skin color image under various illuminants.

visually the skin color and its reproduction under the same viewing conditions. Then, the skin color image is reproduced colorimetrically both on a CRT display and hardcopy. Here, note that the color appearance on a CRT display is different from the color appearance on a 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 corre-

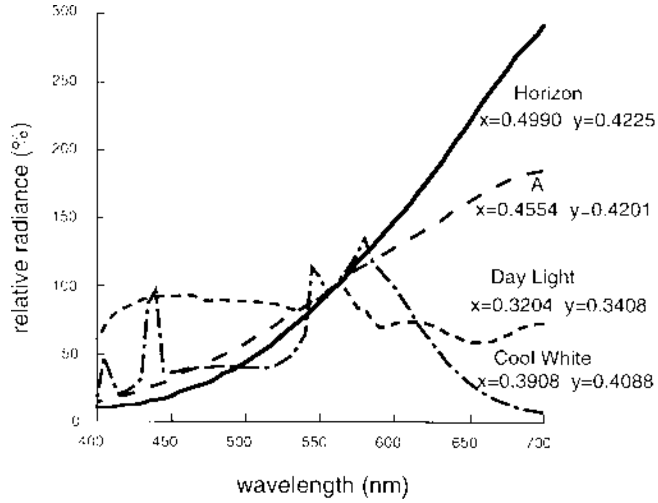


Figure 3. Measured relative spectral radiance of the illumination lamps in the experimental booth.

sponding color reproduction method for skin color. By using color appearance models, the tristimulus values X_a, Y_a, and Z_a after 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 the 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 a CRT display by color transform matrix.

Psychophysical Experiment to Select an Optimum Color Appearance Model for the Proposed Method. The optimum color appearance model to predict color reproduction was estimated by psychophysical experiments. The images on a 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's four illuminants were Daylight (6047 K), A (2837 K), Cool White (3957 K), and Horizon (2320 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 1920×1035 pixels were taken[14] by a HDTV camera under Illuminant C. The model was a young Japanese woman. Six skin color patches with the same color in facial pattern were also prepared. The predicted color reproduction for skin color patches and facial pattern images in the viewing booth were displayed on a CRT. The tristimulus values of the six color patches under illuminant A are shown in Table I. Four images, XYZ, von Kries, Fairchild, and CIELAB images were 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

Figure 4. Predicted color appearance of skin color patches under various illuminants: (a) prediction for illuminant A; (b) prediction for illuminant Horizon; (c) prediction for illuminant Cool White; and (d) prediction for illuminant Daylight.

TABLE I. The Tristimulus Values of the Six Skin Color Patches under Illuminant A

Patch	X	Y	Z
1	105	90	20
2	72	66	18
3	75	70	19
4	38	37	12
5	47	45	13
6	72	61	14

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 the 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 used 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° such that the observers can only see one 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 on the CRT display or in the illumination booth, were observed with both eyes. The observers were asked to look at the skin color print in the booth for about a minute, as long as necessary to stabilize the perception of color. Then the observers compared the memorized color appearance of the hardcopy with the four predicted XYZ, von Kries, Fairchild, and CIELAB images displayed on the 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 could 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

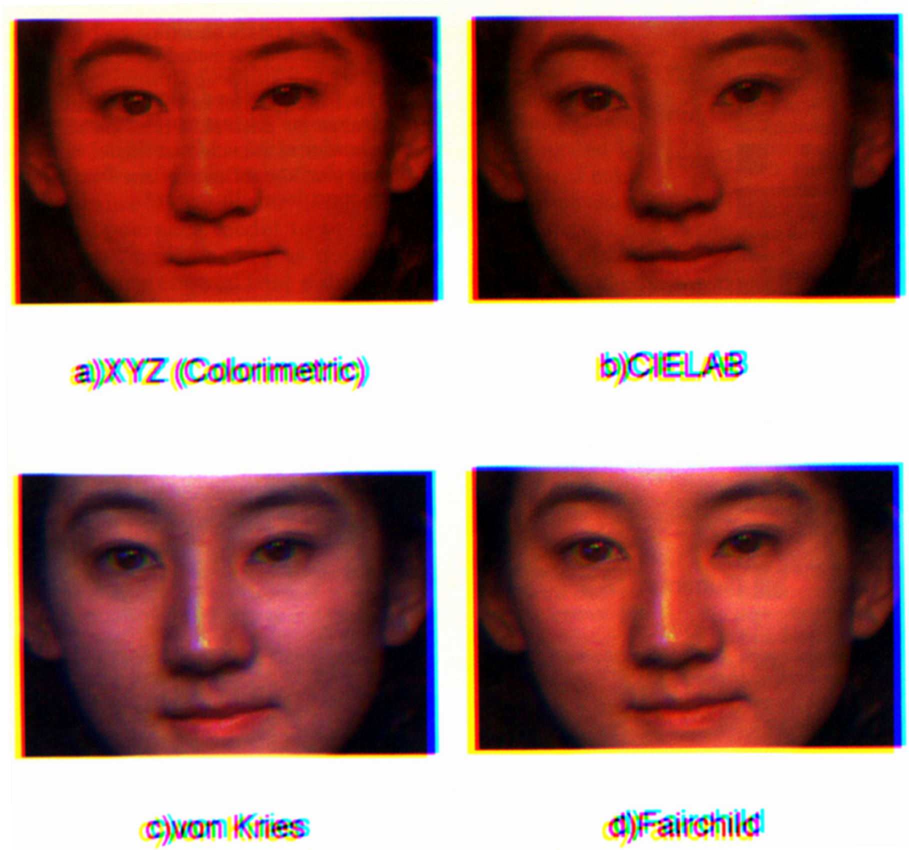


Figure 5. Color appearance predictions of a facial pattern image under illuminant A: (a) XYZ image; (b) CIELAB image; (c) von Kries image; and (d) Fairchild image.

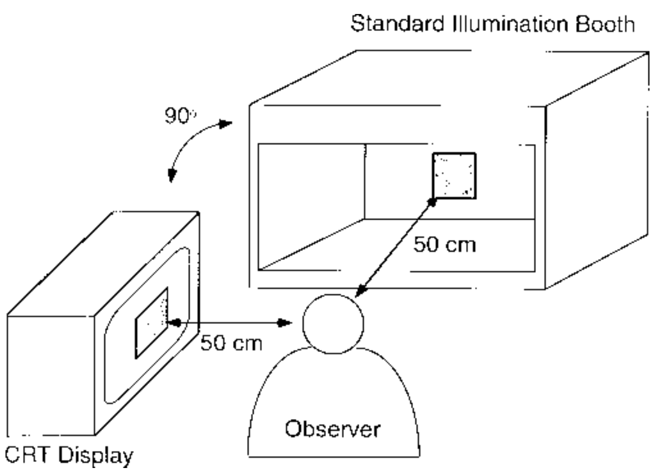


Figure 6. Psychophysical experimental arrangement to compare skin color images on a self-luminous display and a reflection print in a standard illumination booth.

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 and facial pattern images.

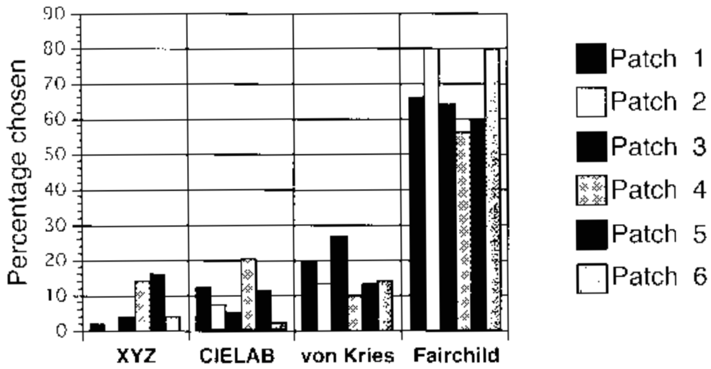
Experimental Results and Discussion

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 the CRT display. From Fig. 7(a), we can see that the color appearance of patches by the Fairchild model was selected most 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 Daylight 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.

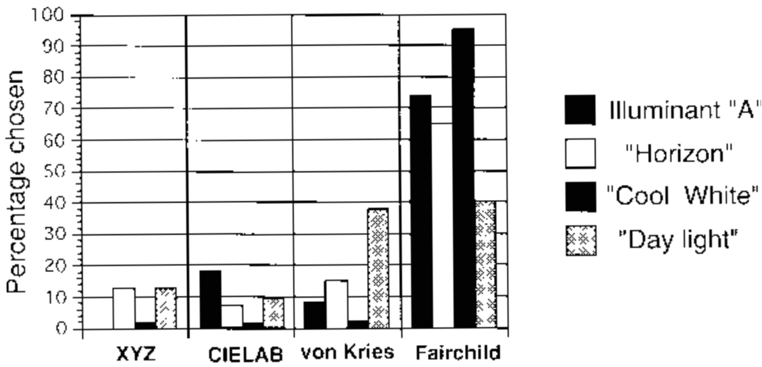
Figure 8(a), on the other hand, shows the percentage of trials on which each reproduced facial pattern image under various illuminants was chosen. The Fairchild model was selected most as the best one. As a result, in an average of 43% of the trials, the observers choose the Fairchild model as the best. 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, no significant difference of experimental results existed among illuminants for each model.

Comparing Fig. 7 and 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 were 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 memorization. The color appearance of facial skin will depend highly on individual memorization.

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

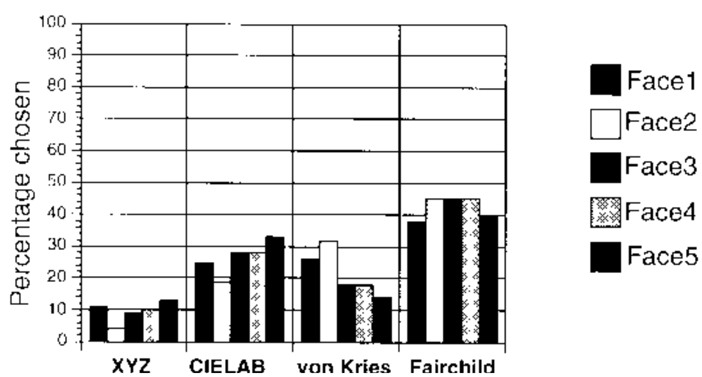


(a)

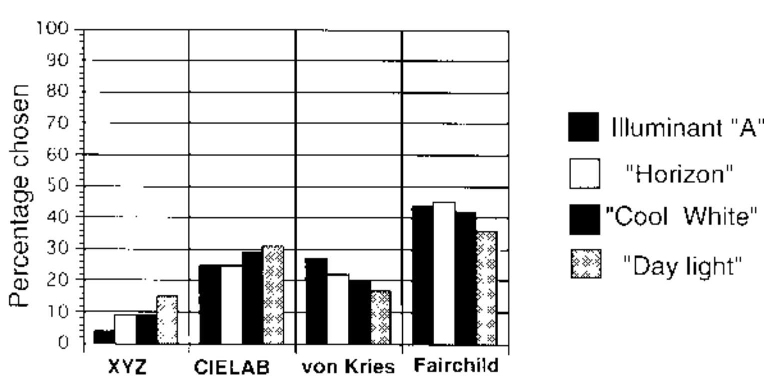


(b)

Figure 7. Percentage of trials on which each reproduced skin color patch was selected on a CRT display compared with a hardcopy under various illuminants: (a) selected model in the prediction of the color appearance for each skin color patch under various illuminants; (b) selected model in the prediction of the color appearance of six skin color patches for each considered illuminant.



(a)



(b)

Figure 8. Percentage of trails on which each reproduced facial pattern image was selected on a CRT display compared with a hardcopy under various illuminants: (a) selected model in the prediction of the color appearance for each facial pattern image under various illuminants; (b) selected model in the prediction of the color appearance of five facial pattern images for each considered illuminant.

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, an optimum color appearance model to predict color reproduction of facial pattern images was not found. The results of the experiments showed that a difference exists 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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