COLOR REPRODUCTION OF FACIAL PATTERN AND ENDOSCOPIC IMAGE BASED ON COLOR APPEARANCE MODELS

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Dedicated to my parents
COLOR REPRODUCTION OF FACIAL PATTERN AND ENDOSCOPIC IMAGE BASED ON COLOR APPEARANCE MODELS

A dissertation submitted to the Graduate School of Science and Technology of Chiba University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

by

Francisco Hideki Imai

December 1996
Declaration

This is to certify that this work has been done by me and it has not been submitted elsewhere for the award of any degree or diploma.

Countersigned                          Signature of the student

Yoichi Miyake, Professor  Francisco Hideki Imai
The undersigned have examined the dissertation entitled
COLOR REPRODUCTION OF FACIAL PATTERN AND ENDOSCOPIC IMAGE
BASED ON COLOR APPEARANCE MODELS

presented by _______Francisco Hideki Imai___________, a candidate for the degree of
Doctor of Philosophy, and hereby certify that it is worthy of acceptance.

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Hirohisa Yaguchi, Professor

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Abstract

In recent years, many imaging systems have been developed, and it became increasingly important to exchange image data through the computer network. Therefore, it is required to reproduce color independently on each imaging device. In the studies of device independent color reproduction, colorimetric color reproduction has been done, namely color with same chromaticity or tristimulus values is reproduced. However, even if the tristimulus values are the same, color appearance is not always same under different viewing conditions. Therefore we must introduce color appearance prediction for color reproduction of image.

In this dissertation, a new color reproduction method based on color appearance prediction is introduced for color reproduction of facial pattern and endoscopic image.

First, spectral reflectance of skin color was analyzed by principal component analysis, and it was shown that the spectral reflectance of skin can be estimated by three principal components. On the basis of these experimental results, spectral reflectances of facial pattern taken by HDTV camera was estimated, and computer simulation of colorimetric color reproduction has been done using those obtained spectral reflectances.

Color appearance models of von Kries, Fairchild, LAB were also introduced to this color reproduction algorithm. The image calculated by those models were compared with the color hardcopies under various illuminants (“A”, “Day Light”, “Horizon”, and “Cool White”) using memory matching technique. It was found that the Fairchild model is most significant to estimate the color appearance of skin color chart under different illuminants. However, the model was not significant to apply to estimation of color appearance in facial pattern. Therefore, modified Fairchild model was introduced to estimate the color appearance of facial pattern. It was shown in psychophysical experiments that the model can estimate well the color appearance of facial pattern compared to other models.
These experiments have been done in the dark environment. However, the practical image on a CRT is usually watched under the environmental illuminant. We must apply color appearance models to reproduce image on a CRT under various illuminants, specially for remote diagnosis of endoscopic images. It is necessary to do a gamut-mapping for image which cannot be reproduced in gamut of CRT. However, up to this time, there is not any way to quantify how gamut-mapping affects the perceived color appearance. A psychophysical metric based on Mahalanobis distance was introduced to evaluate the influence of gamut-mapping in the color appearance instead of conventional color difference. The distance is calculated by covariance matrix of metric lightness, chroma and hue angle obtained by psychophysical experiments.
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CHAPTER 1

INTRODUCTION

Studies of color have been introduced in human life and culture since the beginning of recorded history. Figure 1 shows a diagram of the history of color research.

Figure 1. History of the color research.

In the pre-scientific color studies, Chinese and Greek philosophers only speculated on the nature of color. During the 15th century, color organization and representation were searched.

The color science began with the establishment of a correspondence between color and its physical stimuli in the 17th century. In the 19th century, the advance of
sciences such as physics and chemistry\textsuperscript{1} contributed for the development of color science. The color science also developed with the advances in the study of physiology and psychophysics.\textsuperscript{2} CIE (Commission Internationale de l’Eclairage) specified the colorimetry in 1931 giving a physical relationship between measured stimulus and color response based on a standard observer. However, the CIE colorimetry cannot predict the appearance of color well, because it is based on adapted eyes in pre-defined laboratory conditions, unlike the environment where most colors are seen. The specification\textsuperscript{3} and prediction\textsuperscript{4} of color appearance have been studied in the last 20 years. The study of color appearance considers the influence of environmental factors in the sensation of color.

The increasing speed of computing equipment and devices, scanner, digital camera, printer and CRT display (CRT), allowed the development of techniques\textsuperscript{5} for color imaging. The color science is applied to color imaging to produce cross-media reproductions. It also gives new tools to the color scientists with which they can improve the studies of human color vision.

A new challenge in color imaging systems is to match the color appearance of original scene with reproduced images. In the area of multimedia where we can access color images through the world wide network of computers, the WYSIWYG (what you see is what you get) fidelity in the reproduction of color has become very important. The traditional cross-media reproduction systems\textsuperscript{6,7} does not consider the original scene. The reproduction of the colors in the original scene can be achieved considering original spectral reflectances.\textsuperscript{8} The reproduction of the skin color appearance is also important to the cosmetic industry.

The color appearance reproduction of the original scene is also very important in the area of telemedicine such as diagnosis of electronic endoscopic image. The endoscopic image is not always viewed in a dark environment, and viewing condition is
dependent on the environment of the hospital. In remote diagnosis, however, the endoscopic images are usually sent to physicians in various illuminated environments. Therefore, we need to consider the outer illuminant condition in the color reproduction system. Unfortunately, the processed endoscopic images cannot always be represented inside the color gamut of CRT particularly due to the saturation in the red channel. In such cases, gamut mapping is required. A new challenge in the endoscopic image reproduction system is to evaluate the influence of gamut-mapping in the color appearance of the reproduced image.

1.1 Color reproduction on CRT and hardcopy
The accurate reproduction on CRT and hardcopy has been studied by many researchers.\textsuperscript{9-11} In the following subsections some types of color reproduction are described.

1.1.1 Colorimetric color reproduction
The study of color science developed in the last century with the advance of physics and physiology.\textsuperscript{12-21} These studies constituted the base of the colorimetry.\textsuperscript{22} The colorimetry is obtained by measurement of chromatic properties of the objects by instruments such as spectrophotometer and colorimeter.\textsuperscript{23}

In colorimetric color reproduction, chromaticities and relative luminances of reproduced color are equal to those of the original.\textsuperscript{24} It is possible to achieve device independent color reproduction, in matching the chromaticities and relative luminances of the original with the reproduced images.

1.1.2 Color appearance models
Colorimetric color reproduction works well to reproduce the appearance of colors if the reproduction is viewed under the identical viewing condition of the original image.
However, the use of colorimetric color reproduction is not enough to predict the appearance of colors under various environmental conditions. There are many environmental factors which give the influence upon the appearance of colors such as the illuminant,\textsuperscript{25-27} effect of background and surround,\textsuperscript{28-32} and the size of the colored area\textsuperscript{33}. 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.\textsuperscript{34-37}

There are two types of chromatic adaptation mechanisms: sensory and cognitive.\textsuperscript{38} Sensory mechanisms are based on the sensitivity control in the photoreceptors and neurons in the first stages of the visual system and considers changes in the white point, luminance of illuminant and other aspects of the viewing conditions. Many models have been proposed to measure the appearance of color.\textsuperscript{39-46} The first model of sensory chromatic adaptation was proposed by Johaness von Kries.\textsuperscript{47,48} Subsequent models of chromatic adaptation proposed by C. J. Bartleson,\textsuperscript{49} K. Richter,\textsuperscript{50} R. W. G. Hunt,\textsuperscript{51-54} Y. Nayatani and coworkers,\textsuperscript{55-64} M. D. Fairchild,\textsuperscript{65,66} M. R. Luo and coworkers\textsuperscript{67-69}. Color spaces such as CIELUV\textsuperscript{70}, CIELAB,\textsuperscript{70} RLAB,\textsuperscript{38,71,72} LLAB\textsuperscript{73,74} are also used to predict color appearance. There is also neural models such as the ATD model proposed by S. L. Guth.\textsuperscript{75-77} Another color appearance model is the Retinex theory proposed by E. Land that considers a spatial distribution of all pixels in the field of view.\textsuperscript{78-80} On the other hand, cognitive mechanisms are influenced by observers’ knowledge of image content. The quantification of the cognitive mechanisms is very complex because its psychological nature. Then, no model has been proposed for cognitive mechanisms.

Various color appearance models have been applied to color reproduction of complex images\textsuperscript{81} and evaluated by RIT group.\textsuperscript{38,82-84} These experiments show that a
perfect color appearance model is not available and each model has advantages and disadvantages.

1.1.3 Limitation of the conventional color reproduction methods

The conventional color reproduction methods have three considerable limitations.

First, these methods cannot reproduce correctly the color appearance of the original scene under various illuminants on CRT and hardcopy using only three input channels due to the occurrence of metameric pairs\(^\text{24}\) of original and reproduced image. These metameric pairs are stimuli that are visually identical but spectrally different. A method to estimate the spectral composition of the color stimulus from the input signals is required to predict the metamerism in the reproduction on CRT and hardcopy under various illuminants.

Second, many reproduction methods using color appearance models have been proposed. However, none of them has been applied specifically to skin color that is one of the most important colors for the evaluation of reproduction quality. A comparative experiment between color patches and complex images is also not available for reproduction systems using color appearance models.

Third, some of these systems include gamut-mapping to reproduce images inside the color gamut of CRT displays. However, these methods do not consider yet how gamut-mapping actually modifies the color appearance of the reproduced image. It is desirable to minimize the effect of gamut-mapping in the color appearance reproduction. Then, a perceptual metric based on psychophysical experiments is required to quantify the effect of gamut-mapping on the color appearance of reproduced images.
1.2 Purpose and approach of this research

The purpose of this dissertation is to match the color appearance of an original scene under various illuminants with its reproductions on CRT and hardcopy. In this dissertation, facial pattern and endoscopic image are considered as original scene. Particularly, this study examines the performance of chromatic adaptation models for facial pattern image. This study also investigates the evaluation of gamut mapping influence on the color appearance of endoscopic image reproduced on a CRT under environmental illumination. The gamut-mapping is required in endoscopic images because these images generally have saturation of the red channel on CRT due to their reddish nature.

As a first approach to this color appearance matching, the spectral reflectance of original scene is estimated using the principal component analysis. Then, the estimated spectral reflectance is used to predict the tristimulus values of the original scene under various illuminants. The predicted tristimulus values are reproduced on hardcopy by a printer calibration using a database of spectral reflectance. Chromatic adaptation models are introduced to reproduce the color appearance of hardcopy on CRT.

Next, reproduction on CRT of skin color patches and facial pattern images using various color appearance models are compared by psychophysical experiments. The performance of color appearance models is compared for various illuminants and differences between reproduction of skin color patches and facial pattern image are examined to find an effective model for facial pattern reproduction.

A perceptual distance using covariance matrix for CIELUV metric lightness, chroma and hue angle is defined based on Mahalanobis distance. This distance is applied to evaluate various gamut-mapping techniques required to reproduce endoscopic image on CRT under environmental illumination.
1.3 Organization of this dissertation

In Chapter 2, a technique for two-dimensional prediction of the spectral reflectance of facial pattern from the RGB three channel image taken by HDTV camera is proposed based on principal component analysis. Chapter 3 shows a method to reproduce colorimetrically facial pattern images under various illuminants on CRT in a dark environment, and Chapter 4 describes a method to reproduce colorimetrically facial pattern images as hardcopy. Chapter 5 presents a color reproduction based on color appearance models and psychophysical experiments are performed to evaluate various color appearance models. In Chapter 6, a modified Fairchild chromatic adaptation model for facial pattern images is introduced. In Chapter 7, a color appearance reproduction of endoscopic images on a CRT under various illuminants is described and a perceptual color distance based on Mahalanobis distance is introduced to evaluate gamut-mapping. In Chapter 8, the conclusion and the summary of the proposed color reproduction methods are presented.
CHAPTER 2

PREDICTION OF SPECTRAL REFLECTANCE OF A FACIAL PATTERN IMAGE TAKEN BY HDTV CAMERA

2.1 Introduction
Spectral reflectance of the object should be measured to predict the color of object under various illuminants. The spectral reflectance can be represented in a multidimensional space. Generally, we can obtain only three-channel data from input devices. The estimation from three-dimensional space to multi-dimensional space can be achieved using principal components of spectral reflectance.\textsuperscript{85-89} In this chapter, a method to predict the spectral reflectance of a portrait image taken by a HDTV camera is described.

2.2 Principal component analysis of the spectral reflectances of human skin and their linear approximation
Ojima and his coworkers measured one hundred eight spectral reflectances of skin in human face for 54 Mongolians (Japanese women) who are between 20 and 50 years old.\textsuperscript{90} The Munsell values of the skins had a range as follows; $H=2$YR-8YR, $V=5$-7, $C=2$-5, and the distribution of these skin colors in CIE 1976 L*a*b* color space is shown in Fig. 2.
Figure 2. Distribution of skin colors used in principal component analysis.

The spectral reflectances were measured at intervals of 5 nm between 400 nm and 700 nm. Therefore, the spectral reflectance is described as vectors $o$ in 61-dimensional vector space. Figure 3 shows the averaged spectral reflectance of human skin, and these values are given in Table 1.

Figure 3. Averaged spectral reflectance of human skin.
Table 1. Averaged spectral reflectance of the sampled human skin.

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The covariance matrix of the spectral reflectance was calculated for the principal component analysis. The eigenvectors of the covariance matrix are named as principal component vectors. Then, the spectral reflectance of human skin can be expressed as a linear combination of the principal component vectors as follows:

\[
\mathbf{o} = \bar{\mathbf{o}} + \sum_{i=1}^{61} \alpha_i \mathbf{u}_i,
\]  

(2-1)
where $\bar{\sigma}$ is the averaged spectral reflectance, $u_i$ ($i=1...61$) are the eigenvectors and $\alpha_i$ ($i=1...61$) are the eigenvalues corresponding to the eigenvectors $u_i$ ($i=1...61$) respectively. The eigenvectors are combined in order of magnitude of the eigenvalues.

The cumulative contribution rates of the principle component vectors are shown in Fig. 4.

**Figure 4.** Cumulative contribution ratio of principal components of the skin spectral reflectance.

From this figure, we can see that the cumulative contribution rate from first to third components is about 99.5%. Then, the spectral reflectance of human skin can be represented approximately 99.5% by using linear combination of three principal components $u_1, u_2, u_3$. The three principal components are shown in Fig. 5.
Figure 5. The first, second and third principal components of the spectral reflectance of skin.

The values of the principal components are given in Table 2. Therefore the Eq. (2-1) can be represented approximately as follows:

\[
o \cong \bar{o} + \sum_{i=1}^{3} \alpha_i u_i = \bar{o} + \begin{pmatrix} u_1 & u_2 & u_3 \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix}.
\]  
(2-2)
Table 2. The first, second and third principal components of the spectral reflectance of human skin.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>1st Principal Component</th>
<th>2nd Principal Component</th>
<th>3rd Principal Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>2.258</td>
<td>0.326</td>
<td>-0.514</td>
</tr>
<tr>
<td>405</td>
<td>2.232</td>
<td>0.306</td>
<td>-0.506</td>
</tr>
<tr>
<td>410</td>
<td>2.207</td>
<td>0.284</td>
<td>-0.497</td>
</tr>
<tr>
<td>415</td>
<td>2.177</td>
<td>0.267</td>
<td>-0.491</td>
</tr>
<tr>
<td>420</td>
<td>2.149</td>
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<td>0.242</td>
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<td>0.234</td>
<td>-0.488</td>
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<tr>
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<td>-0.488</td>
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<tr>
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<td>0.161</td>
<td>-0.510</td>
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<tr>
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<td>0.102</td>
<td>-0.533</td>
</tr>
<tr>
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<td>2.619</td>
<td>0.041</td>
<td>-0.557</td>
</tr>
<tr>
<td>455</td>
<td>2.665</td>
<td>0.000</td>
<td>-0.572</td>
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<td>-0.490</td>
</tr>
<tr>
<td>525</td>
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<tr>
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<tr>
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<td>3.950</td>
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</tr>
<tr>
<td>Wavelength (nm)</td>
<td>1st Principal Component</td>
<td>2nd Principal Component</td>
<td>3rd Principal Component</td>
</tr>
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<td>-------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
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<tr>
<td>700</td>
<td>2.202</td>
<td>1.124</td>
<td>0.550</td>
</tr>
</tbody>
</table>

Figure 6 shows a comparison between measured and predicted relative spectral reflectance of human skin by principal component analysis. From this figure it is possible to conclude that the linear approximation of the spectral reflectance using three principal components works well.

Then, the spectral reflectance of each pixel of image can be predicted from the tristimulus values of each pixel and the spectral radiance of the illuminant, as is performed in electronic endoscopic images\textsuperscript{91}.
2.3 Estimation of the skin spectral reflectance

Considering the result of above principal component analysis, we can estimate the spectral reflectance of skin using the tristimulus values. The tristimulus values can be easily measured by a colorimeter. The spectral reflectance of skin is estimated as follows. As well known, the tristimulus values $X$, $Y$, $Z$ can be calculated by Eq. (2-3).

\begin{align}
X &= K \sum_{\lambda = 400}^{700} E(\lambda) \bar{x}(\lambda) O(\lambda), \\
Y &= K \sum_{\lambda = 400}^{700} E(\lambda) \bar{y}(\lambda) O(\lambda), \\
Z &= K \sum_{\lambda = 400}^{700} E(\lambda) \bar{z}(\lambda) O(\lambda),
\end{align}

\hspace{1cm} (2-3a) \hspace{1cm} (2-3b) \hspace{1cm} (2-3c)
where $\lambda$ is the wavelength, $O(\lambda)$ is the spectral reflectance, $E(\lambda)$ is the spectral radiance of the illuminant, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are color matching functions and $K$ is a coefficient given by Eq. (2-4).

$$K = \frac{1}{700} \int_{\lambda = 400}^{700} E(\lambda) \tau(\lambda) d\lambda$$

By vector notations, Eq. (2-3) can be expressed as follows:

\begin{align*}
X &= Ke' \bar{X} o, \quad (2-5a) \\
Y &= Ke' \bar{Y} o, \quad (2-5b) \\
Z &= Ke' \bar{Z} o, \quad (2-5c)
\end{align*}

where $[.]'$ represents the transpose of $[.]$, the vectors $e, o$ are vector notations of $E(\lambda)$ and $O(\lambda)$ respectively, and the matrixes $\bar{X}$, $\bar{Y}$, $\bar{Z}$ are represented as follows:

\begin{align*}
\bar{x}(\lambda) &\rightarrow \bar{X} = \begin{bmatrix}
\bar{x}_1(\lambda_1) & O \\
\bar{x}_2(\lambda_2) & \ddots \\
O & \bar{x}_n(\lambda_n)
\end{bmatrix}, \quad (2-6a) \\
\bar{y}(\lambda) &\rightarrow \bar{Y} = \begin{bmatrix}
\bar{y}_1(\lambda_1) & O \\
\bar{y}_2(\lambda_2) & \ddots \\
O & \bar{y}_n(\lambda_n)
\end{bmatrix}, \quad (2-6b) \\
\bar{z}(\lambda) &\rightarrow \bar{Z} = \begin{bmatrix}
\bar{z}_1(\lambda_1) & O \\
\bar{z}_2(\lambda_2) & \ddots \\
O & \bar{z}_n(\lambda_n)
\end{bmatrix}. \quad (2-6c)
\end{align*}
From Eq. (2-2), the Eq. (2-5) can be written as,

\[ X \cong K e^t \bar{X} \beta + (u_1 \ u_2 \ u_3) (\alpha_1 \ \alpha_2 \ \alpha_3) \]  
\[ Y \cong K e^t \bar{Y} \beta + (u_1 \ u_2 \ u_3) (\alpha_1 \ \alpha_2 \ \alpha_3) \]  
\[ Z \cong K e^t \bar{Z} \beta + (u_1 \ u_2 \ u_3) (\alpha_1 \ \alpha_2 \ \alpha_3) \]  

The Eq. (2-7) can be rewritten as follows:

\[ X \cong K e^t \bar{X} o + K e^t (\bar{X} u_1 \ \bar{X} u_2 \ \bar{X} u_3) (\alpha_1 \ \alpha_2 \ \alpha_3) \]  
\[ Y \cong K e^t \bar{Y} o + K e^t (\bar{Y} u_1 \ \bar{Y} u_2 \ \bar{Y} u_3) (\alpha_1 \ \alpha_2 \ \alpha_3) \]  
\[ Z \cong K e^t \bar{Z} o + K e^t (\bar{Z} u_1 \ \bar{Z} u_2 \ \bar{Z} u_3) (\alpha_1 \ \alpha_2 \ \alpha_3) \]  

We can consider the first term of Eq. (2-8) as a contribution of the averaged spectral reflectance to the tristimulus values, and the second term as a contribution of three eigenvectors. Then, we can rewrite the Eq. (2-8) as follows:

\[ \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \cong \begin{bmatrix} \bar{X} \\ \bar{Y} \\ \bar{Z} \end{bmatrix} o + \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \\ X_2 \\ Y_2 \\ Z_2 \\ X_3 \\ Y_3 \\ Z_3 \end{bmatrix} (\alpha_1 \ \alpha_2 \ \alpha_3) \]
where $\overline{X}$, $\overline{Y}$, $\overline{Z}$ are the averaged tristimulus values and $X_i, Y_i, Z_i$ ($i=1,2,3$) are the tristimulus values corresponding to the three eigenvectors of skin spectral reflectance. Then, the eigenvalues $\alpha_1$, $\alpha_2$, and $\alpha_3$ are given by

$$
\begin{bmatrix}
\alpha_1 \\
\alpha_2 \\
\alpha_3
\end{bmatrix} = \begin{bmatrix}
X_1 & X_2 & X_3 \\
Y_1 & Y_2 & Y_3 \\
Z_1 & Z_2 & Z_3
\end{bmatrix}^{-1} \begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} - \begin{bmatrix}
\overline{X} \\
\overline{Y} \\
\overline{Z}
\end{bmatrix}.
$$

(2-10)

The spectral reflectance of human skin can be estimated by above eigenvalues and three principal components by Eq. (2-2).

**2.4 Characterization of HDTV camera**

Figure 7 shows the schematic diagram of the image acquisition and the estimation of the spectral reflectance in each pixel of the image based on the characterization of the HDTV camera. In the previous sections, it was shown how spectral reflectances of human face can be estimated from the device independent tristimulus values $X, Y, Z$ using Eqs. (2-2) and (2-10). In this section, $X, Y, Z$ in each pixel of original scene is calculated from the $R, G, B$ three color channels of the HDTV camera.

The output color channel values $R_o, G_o, B_o$ of an ideal HDTV camera can be given by the Eq. (2-11),

$$
R_o = \sum_{\lambda=400}^{700} E(\lambda) \tilde{r}(\lambda) O(\lambda),
$$

(2-11a)

$$
G_o = \sum_{\lambda=400}^{700} E(\lambda) \tilde{g}(\lambda) O(\lambda),
$$

(2-11b)

$$
B_o = \sum_{\lambda=400}^{700} E(\lambda) \tilde{b}(\lambda) O(\lambda),
$$

(2-11c)

where $\tilde{r}(\lambda), \tilde{g}(\lambda), \tilde{b}(\lambda)$ are the spectral sensitivities of the camera, $E(\lambda)$ is the spectral radiance of the illuminant and $O(\lambda)$ is the spectral reflectance of the object.
First, second and third principal components of the spectral reflectance of human skin

However, the actual output color channel values $R'$, $G'$, $B'$ of a HDTV camera is given by Eq. (2-12):

\begin{align*}
R' &= K_r \cdot f_r(R_o), & (2-12a) \\
G' &= K_g \cdot f_g(G_o), & (2-12b) \\
B' &= K_b \cdot f_b(B_o). & (2-12c)
\end{align*}
where \( f_r, f_g, f_b \) are non-linear functions, and \( K_r, K_g, K_b \) are white balance constants.

The non-linearity between \( R, G, B \) level and luminance was linearized using the following quadratic equations:\(^2\)

\[
R' = -5.50 + 4.26 \times 10^{-1} R_o + 2.04 \times 10^{-3} R_o^2, \quad (2-13a)
\]

\[
G' = -6.06 \times 10^{-1} + 2.90 \times 10^{-3} G_o + 2.66 \times 10^{-3} G_o^2, \quad (2-13b)
\]

\[
B' = -7.37 \times 10^{-1} + 2.31 \times 10^{-1} B_o + 3.11 \times 10^{-3} B_o^2. \quad (2-13c)
\]

Generally the \( r(\lambda), \ g(\lambda), \ b(\lambda) \) are different from visual color matching functions. Then, it is necessary to find a color transformation function that gives the device independent tristimulus values \( X, Y, Z \) from the HDTV camera output channels \( R', G', B' \). Ojima and his coworkers showed that a color transformation matrix \( M_1 \) shown in Eq. (2-14) gives sufficient accuracy for the HDTV camera calibration:\(^2\)

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} = M_1 \begin{pmatrix}
R' \\
G' \\
B'
\end{pmatrix}
\quad (2-14)
\]

This matrix \( M_1 \) can be determined by the following technique. The tristimulus values of a series of color patches are measured by a colorimeter and are digitized by HDTV camera. The values of \( R', G', B' \) channels in Eq. (2-13) are calculated from the output values \( R, G, B \) of the HDTV camera. The matrix \( M_1 \) can be determined by the multiple regression analysis of measured \( X, Y, Z \) tristimulus values and calculated \( R', G', B' \) color channel values of digitized color patches.

The tristimulus values \( X, Y, Z \) of thirty-nine selected patches of Japanese skin color were measured by a spectrophotometer (Minolta CM1000). The Munsell values of the patches have a range as follows; \( H=0YR-10YR, V=5-8, C=2-5 \).
The skin color patches were digitized under Metal halide lamp (RDS, with color temperature of 5,700 K) illumination at 2° field of view by a HDTV camera (Nikon HQ1500C). The calculated color transform matrix $M_1$ is shown in Eq. (2-15).

$$M_1 = \begin{pmatrix}
2.09 \times 10^{-1} & 5.37 \times 10^{-2} & 5.09 \times 10^{-2} & -2.41 \\
1.17 \times 10^{-1} & 2.07 \times 10^{-1} & -4.80 \times 10^{-3} & -2.05 \\
7.69 \times 10^{-4} & 7.67 \times 10^{-3} & 3.65 \times 10^{-1} & -0.827
\end{pmatrix}$$ (2-15)

The accuracy of this color transformation is verified by $\Delta E^{*ab}$ color difference\textsuperscript{93,94} between the tristimulus values $X_m$, $Y_m$, $Z_m$ and $X_e$, $Y_e$, $Z_e$. $X_m$, $Y_m$, $Z_m$ are measured using a spectrophotometer (Minolta CM1000) and $X_e$, $Y_e$, $Z_e$ are estimated using the matrix $M_1$ in Eq. (2-15). The color difference is calculated as shown in Eq. (2-16)

$$\Delta E^{*ab} = \sqrt{(L_m^* - L_e^*)^2 + (a_m^* - a_e^*)^2 + (b_m^* - b_e^*)^2},$$ (2-16)

where ($L_m^*$, $a_m^*$, $b_m^*$) and ($L_e^*$, $a_e^*$, $b_e^*$) are the CIELAB 1976 metric lightness and the coordinates calculated from $X_m$, $Y_m$, $Z_m$ and $X_e$, $Y_e$, $Z_e$, respectively.

The averaged color difference $\Delta E^{*ab}$ was 1.0 and the maximum color difference $\Delta E^{*ab}_{\text{max}}$ was 2.3. This result shows that the color transformation by matrix $M_1$ in Eq. (2-14) has sufficient accuracy to calculate the $X$, $Y$, $Z$ necessary to estimate the spectral reflectance.
2.5 Conclusion

In this chapter, a method to predict the spectral reflectance of a portrait image digitized by a HDTV camera is described. Spectral reflectance of Japanese women’s skin was estimated with 99.5% accuracy using the first, second and third principal components of the spectral reflectance of skin. The obtained color difference less than 2.30 indicates that the camera calibration was performed with sufficient accuracy to calculate the tristimulus values.
CHAPTER 3

COLORIMETRIC COLOR REPRODUCTION OF FACIAL PATTERN IMAGE ON CRT

3.1 Introduction

Figure 8 shows a schematic diagram of colorimetric color reproduction for facial pattern image on CRT in a dark environment. A facial pattern image is taken by a HDTV camera under illuminant with spectral radiance $E_1(\lambda)$.

Figure 8. Diagram of the proposed colorimetric color reproduction method to predict the tristimulus values of facial pattern image under various illuminants on a CRT in a dark environment.
Chapter 3

The tristimulus values $X$, $Y$, $Z$ of the portrait image is calculated from three channels $R$, $G$, $B$ values of the HDTV camera using transformation matrix $M_1$ as shown in the previous chapter. In the proposed method, the two-dimensional spectral reflectance of the object in the scene is calculated using the tristimulus values of the digitized image based on the principal component analysis of the spectral reflectance of human skin. Then, the tristimulus values of the image under a new illuminant with spectral radiance $E_2(\lambda)$ can be predicted from the estimated spectral reflectance. The $R_c$, $G_c$, $B_c$ input values of CRT is calculated by color transform matrix $M_2$ obtained by the colorimetric calibration of the CRT.

3.2 Tristimulus values of facial pattern image

The tristimulus values $X'$, $Y'$, $Z'$ of skin color under a selected illuminant can be easily calculated from the estimated spectral reflectance $O(\lambda)$ and the spectral radiance $E_2(\lambda)$ of the illuminant. The tristimulus values $X'$, $Y'$, $Z'$ are calculated as follows:

$$X' = K \int_{\lambda=400}^{\lambda=700} O(\lambda) E_2(\lambda) \bar{x}(\lambda) d\lambda \quad (3-1a)$$

$$Y' = K \int_{\lambda=400}^{\lambda=700} O(\lambda) E_2(\lambda) \bar{y}(\lambda) d\lambda \quad (3-1b)$$

$$Z' = K \int_{\lambda=400}^{\lambda=700} O(\lambda) E_2(\lambda) \bar{z}(\lambda) d\lambda \quad (3-1c)$$

3.3 Calibration of CRT

Many methods to calibrate a computer controlled color monitor have been proposed. In general cases, it is possible to define a two-stage model for CRT to transform $R_c$, $G_c$, $B_c$ input values to the tristimulus values $X'$, $Y'$, $Z'$. The first stage is a nonlinear transformation from $R_c$, $G_c$, $B_c$ values to phosphor luminances produced by digital-to-
analog converter. The second stage is a linear transformation where the monitor phosphor luminances are transformed to the \( X', Y', Z' \) values. The calculation of the transformation \( M_2 \) in the schematic diagram of Fig. 8 was performed as follows.

A steady CRT with fixed luminance, contrast, white point, and gamma is used. Color patches are displayed on the CRT in a dark environment to avoid interference with external light sources. The luminance \( L \) and the tristimulus values \( X, Y, Z \) were measured at the displayed color patches in each channel. The luminance colorimeter is adjusted at the position of the observer eyes because the angle of incidence of the beams can influence the measurements.\(^{104}\)

The relationship between the input level and luminance is plotted and the Eq. (3-2) can be derived from curve fitting for quadratic curves.

\[
L_R = a_0 R_c^2 + a_1 R_c + a_2 \quad (3-2a)
\]
\[
L_G = b_0 G_c^2 + b_1 G_c + b_2 \quad (3-2b)
\]
\[
L_B = c_0 B_c^2 + c_1 B_c + c_2 \quad (3-2c)
\]

These equations show the relationship between the luminance and input levels, where \( L_R, L_G, L_B \) are the luminance of red, green, and blue phosphors respectively, and \( a_i, b_i, c_i \) \((i = 0 \text{ to } 2)\) are coefficients.

The tristimulus values \( X, Y, Z \) on CRT can be decomposed as follows:

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} = \begin{pmatrix}
X_R + X_G + X_B \\
Y_R + Y_G + Y_B \\
Z_R + Z_G + Z_B
\end{pmatrix}, \quad (3-3)
\]

where \( X_i, Y_i, Z_i \) \((i = r, g, b)\) are the tristimulus values corresponding to the emission of red, green, blue phosphor, respectively. A theoretical relationship between \( X-Y, Z-Y \) for each phosphor is given by

\[
X_r = \frac{x_r}{y_r} Y_r, \quad (3-4a)
\]
However the linear curve fitting introduces an offset error in the Eq. (3-4). This error is considered in the following linear equations:

\[
X_R = a_R Y_R + b_R \quad (3-5a)
\]

\[
X_G = a_G Y_G + b_G \quad (3-5b)
\]

\[
X_B = a_B Y_B + b_B \quad (3-5c)
\]

\[
Z_R = c_R Z_R + d_R \quad (3-5d)
\]

\[
Z_G = c_G Z_G + d_G \quad (3-5e)
\]

\[
Z_B = c_B Z_B + d_B \quad (3-5f)
\]

where \(a_i, b_i, c_i, d_i \quad (i = R, G, B)\) are coefficients.

From Eqs. (3-3) and (3-5), the following equation is obtained;

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix}
= \begin{pmatrix}
a_R Y_R + a_G Y_G + a_B Y_B + b_R + b_G + b_B \\
Y_R + Y_G + Y_B \\
c_R Y_R + c_G Y_G + c_B Y_B + d_R + d_G + d_B
\end{pmatrix}.
\]

(3-6)

The Eq. (3-6) can be rewrited as follows;

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix}
= A \begin{pmatrix}
Y_R \\
Y_G \\
Y_B
\end{pmatrix} + \begin{pmatrix}
b_R + b_G + b_B \\
0.0 \\
d_R + d_G + d_B
\end{pmatrix},
\]

(3-7)
where
\[
A = \begin{pmatrix}
    a_R & a_G & a_B \\
    1.0 & 1.0 & 1.0 \\
    c_R & c_G & c_B 
\end{pmatrix},
\]
(3-8)

The luminance can be calculated from the Eq. (3-9) as follows;
\[
\begin{pmatrix}
    L_R \\
    I_G \\
    L_B 
\end{pmatrix}
= 
\begin{pmatrix}
    Y_R \\
    Y_G \\
    Y_B 
\end{pmatrix}
= A^{-1}
\begin{pmatrix}
    X - b_R - b_G - b_B \\
    Y \\
    Z - d_R - d_G - d_B 
\end{pmatrix}.
\]
(3-9)

Then, using the Eqs. (3-3) and (3-8), the transformation from the tristimulus values \(X, Y, Z\) to the input levels \(R_c, G_c, B_c\) can be achieved.

### 3.4 Experiments and their results

Two CRTs (Nanao Flex Scan56T Monitor and AppleColor High-Resolution RGB Monitor Model MO401) with fixed luminance, contrast, white point, and gamma were calibrated. These CRTs will also be used in the experiments of Chapter 7. The setting of the CRTs is shown in Table 3.

<table>
<thead>
<tr>
<th>CRT</th>
<th>Luminance (cd/m²)</th>
<th>Contrast</th>
<th>White point</th>
<th>gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanao Flex Scan56T CRT</td>
<td>93.3</td>
<td>Maximum</td>
<td>D65</td>
<td>1.80</td>
</tr>
<tr>
<td>Apple MO401 CRT</td>
<td>71.5</td>
<td>Maximum</td>
<td>D65</td>
<td>1.80</td>
</tr>
</tbody>
</table>

Twenty-six color patches were displayed on each CRT in a dark environment. The luminance \(L\) and the tristimulus values \(X, Y, Z\) of the displayed color patches in each channel were measured by a luminance colorimeter (TOPCOM BM-7).

Figures 9(a) and 9(b) show the relationship between input levels of CRT and luminance of phosphor for Nanao Flex Scan56T CRT and AppleColor MO401 CRT.
respectively. From Figs. 9(a) and 9(b) it is possible to determine the coefficients shown in Table 4 of the quadratic equation (3-2).

**Figure 9(a).** The relationship between input levels of CRT (Nanao Flex Scan56T) and luminance of phosphor.

Figures 10(a) and 10(b) show the X-Y and Z-Y relationship for each RGB channel of Nanao Flex Scan56T CRT and AppleColor MO401 CRT respectively.
Figure 9(b). The relationship between input levels of CRT (AppleColor MO401) and luminance of phosphor.

Table 4. Coefficients obtained by quadratic curve fitting for CRTs (Nanao FlexScan 56T and AppleColor MO401) in a dark environment.

<table>
<thead>
<tr>
<th>Monitor</th>
<th>Nanao Flex Scan56T</th>
<th>Apple MO401</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>$1.216 \times 10^{-4}$</td>
<td>$1.536 \times 10^{-4}$</td>
</tr>
<tr>
<td>$a_1$</td>
<td>$6.212 \times 10^{-2}$</td>
<td>$1.482 \times 10^{-3}$</td>
</tr>
<tr>
<td>$a_2$</td>
<td>$-5.592 \times 10^{-1}$</td>
<td>$-1.745 \times 10^{-1}$</td>
</tr>
<tr>
<td>$b_0$</td>
<td>$3.270 \times 10^{-4}$</td>
<td>$4.339 \times 10^{-4}$</td>
</tr>
<tr>
<td>$b_1$</td>
<td>$1.863 \times 10^{-1}$</td>
<td>$9.552 \times 10^{-2}$</td>
</tr>
<tr>
<td>$b_2$</td>
<td>$-1.714 \times 10^{0}$</td>
<td>$-7.855 \times 10^{-1}$</td>
</tr>
<tr>
<td>$c_0$</td>
<td>$6.138 \times 10^{-5}$</td>
<td>$5.225 \times 10^{-5}$</td>
</tr>
<tr>
<td>$c_1$</td>
<td>$6.782 \times 10^{-3}$</td>
<td>$8.492 \times 10^{-3}$</td>
</tr>
<tr>
<td>$c_2$</td>
<td>$-1.122 \times 10^{-1}$</td>
<td>$-9.007 \times 10^{-2}$</td>
</tr>
</tbody>
</table>
Figure 10(a). X-Y and Z-Y relationship for each RGB channel of the CRT (Nanao Flex Scan56T).
Figure 10(b). X-Y and Z-Y relationship for each RGB channel of the CRT
(AppleColor MO401).
From Figs. 10(a) and 10(b) it is possible to determine the coefficients shown in Table 5 for linear Eq. (3-7).

**Table 5.** Coefficients obtained by linear curve fitting for CRTs (Nanao FlexScan 56T and AppleColor MO401) in a dark environment.

<table>
<thead>
<tr>
<th>Monitor</th>
<th>Nanao Flex Scan56T</th>
<th>AppleColor MO401</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_R$</td>
<td>$1.773 \times 10^0$</td>
<td>$1.791 \times 10^0$</td>
</tr>
<tr>
<td>$a_G$</td>
<td>$4.882 \times 10^{-1}$</td>
<td>$4.867 \times 10^{-1}$</td>
</tr>
<tr>
<td>$a_B$</td>
<td>$2.429 \times 10^0$</td>
<td>$2.420 \times 10^0$</td>
</tr>
<tr>
<td>$b_R$</td>
<td>$1.372 \times 10^{-1}$</td>
<td>$4.909 \times 10^{-2}$</td>
</tr>
<tr>
<td>$b_G$</td>
<td>$3.714 \times 10^{-2}$</td>
<td>$1.020 \times 10^{-2}$</td>
</tr>
<tr>
<td>$b_B$</td>
<td>$-2.258 \times 10^{-2}$</td>
<td>$2.220 \times 10^{-3}$</td>
</tr>
<tr>
<td>$c_R$</td>
<td>$7.242 \times 10^{-2}$</td>
<td>$7.719 \times 10^{-2}$</td>
</tr>
<tr>
<td>$c_G$</td>
<td>$1.934 \times 10^{-1}$</td>
<td>$1.967 \times 10^{-1}$</td>
</tr>
<tr>
<td>$c_B$</td>
<td>$1.314 \times 10^1$</td>
<td>$1.293 \times 10^1$</td>
</tr>
<tr>
<td>$d_R$</td>
<td>$6.663 \times 10^{-3}$</td>
<td>$2.238 \times 10^{-4}$</td>
</tr>
<tr>
<td>$d_G$</td>
<td>$-5.807 \times 10^{-2}$</td>
<td>$-4.334 \times 10^{-2}$</td>
</tr>
<tr>
<td>$d_B$</td>
<td>$-1.391 \times 10^{-1}$</td>
<td>$3.079 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Five facial pattern images with 1920 by 1035 pixels were taken by a HDTV camera under the same conditions used for camera calibration. The model is a Japanese young woman. The tristimulus values $X'$, $Y'$, $Z'$ were calculated using the estimated
spectral reflectance under four illuminants; “Day Light”, “A”, “Cool White”, and “Horizon”. Those spectral radiances and chromaticities are shown in Fig. 11. The calculated tristimulus values were converted to $R_c$, $G_c$, $B_c$ values and they are displayed on CRT.

![Relative spectral radiant power and chromaticities of four illuminants used in the experiment.](image)

**Figure 11.** Relative spectral radiant power and chromaticities of four illuminants used in the experiment.

Figure 12 shows the hardcopy of the predicted facial pattern printed directly from the input levels $R_c$, $G_c$, $B_c$ without any preprocessing or color correction. Actually, these images should be observed on CRT. We can see that the portrait images under "A" and "Horizon" illuminants seem reddish, because longer wavelength components are predominant in these illuminants as shown in Fig. 11.
Figure 12. A facial pattern image reproduced colorimetrically on CRT under four illuminants; (a) “Horizon,” (b) “A,” (c) “Cool White,” (d) “Day Light” illuminants.
3.5 Conclusion

In this chapter, a colorimetric color reproduction method for portrait image on CRT in a dark environment was proposed. In this method, the tristimulus values of each pixel of the image were calculated using the estimated spectral reflectance, the spectral radiance of the illuminant and the color matching functions. The calculated tristimulus values were transformed to $R, G, B$ values of CRT. A portrait image under various illuminants was reproduced on CRT. The portrait images under “Horizon” and illuminant “A” seem very reddish because the predominance of the long-wavelength components in such illuminants. However, the portrait images under “Horizon” and illuminant “A” do not seem actually so reddish when viewed under such illuminants because the chromatic adaptation is not considered yet in this reproduction method.
CHAPTER 4

COLORIMETRIC COLOR REPRODUCTION OF FACIAL PATTERN IMAGE ON HARDCOPY

4.1 Introduction

Color correction is necessary to match the tristimulus values of hardcopies with those in the original scene. The colorimetric calibration of printers for color correction is difficult because this calibration depends on the observing environment and specially on the illuminants. Various color transform corrections have been proposed for colorimetric calibration.\textsuperscript{6,105,106} In this chapter, the printer calibration is achieved by making color transformation function during the printing process, using the data base of input values to printer and spectral reflectances, measured before the printing.

4.2 Color reproduction method for hardcopy under various illuminants

Figure 13 shows the schematic diagram of the colorimetric color reproduction of facial pattern image on hardcopy under various illuminants. In this reproduction method, the tristimulus values $X''$, $Y''$, $Z''$ of a printed skin color image under an illuminant with spectral radiance $E_3(\lambda)$ were matched to the tristimulus values $X'$, $Y'$, $Z'$ calculated using principal components of the spectral reflectance of the skin. To achieve the matching, the matrix $M_3$ was used to transform the CRT input levels $R_c$, $G_c$, $B_c$ to printer input levels $R_p$, $G_p$, $B_p$. The matrix $M_3$ is a function of the spectral radiance $E_3(\lambda)$ of the illuminant for viewing of hardcopy and this matrix is calculated by multiple regression analysis using a data base of input values to the printer and measured spectral
reflectances. It is noted that we do not need to measure the tristimulus values of the color patches under each illuminant for calibration.

Figure 13. Diagram of the color reproduction method for hardcopy of skin color image under various illuminants.

4.3 Multiple regression analysis using skin spectral reflectances

Figure 14 shows a schematic diagram of the multiple regression analysis using the database. One hundred eight skin color patches were printed using a laser thermal development and transfer printer (Fujix Pictrography 3000) with printer input level $R_p^n$, $G_p^n$, $B_p^n$. The spectral reflectance $O^n(\lambda)$ of each patch was measured by a spectrophotometer (Datacolor Spectraflash 500).

In the on-line calibration, the tristimulus values $X^n$, $Y^n$, $Z^n$ were calculated under a selected illuminant $E_3(\lambda)$ using the data base. The tristimulus values $X'^n$, $Y'^n$, $Z'^n$,
Z" for each patch were transformed to $R^n_c$, $G^n_c$, $B^n_c$ CRT input levels using the transformation matrix $M_2$. The coefficients ($a_{ij}$) ($i=1...3$, $j=1...11$) of matrix $M_3$ in the Eq. (4-1) were determined by multiple regression analysis\textsuperscript{107}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{multiple_regression_diagram.png}
\caption{Diagram of the multiple regression analysis.}
\end{figure}

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. The color difference was calculated between CRT and hardcopy, with and without color transformation.
As shown in Fig. 15, the averaged color difference $\Delta E^*_{ab}$ was 19.9 without the color transformation, and 4.5 with the color transformation. Thereafter, fifty-five skin color patches, not used in multiple regression analysis, were printed with color transformation by $M_3$. The averaged color difference $\Delta E^*_{ab}$ was 4.9. We can conclude that the proposed color transformation is effective to match the skin color between displayed image and hardcopy. The matrix $M_3$ was calculated using a workstation (SPARC station II; Sun micro system Inc.) in an average time of 25 seconds.
4.4 Experimental results

The portraits used in Chapter 3 was reproduced under four kinds of illuminants; “Horizon”, “A”, “Cool White”, and “Day Light” in a standard illumination booth (Macbeth Spectralight II). The spectral radiance of each illuminant is shown in Fig. 11. The portrait images printed using transformation matrix $M_3$ is shown in Fig. 16.
It is noted that the printed images under "A" and "Horizon" illuminants are not reddish as the corresponding portrait images on CRT as shown in Fig. 12 because each image will not be observed under the illuminant used in the calibration. Here, it is also noted that colors of printed portrait images under different illuminants in Fig. 16 are slightly different. If the spectral reflectance of print is as same as the spectral reflectance of human face, there is no difference in the printed images due to the illuminants. Averaged spectral reflectance of printed skin is shown in Fig. 17. It is clear that the spectral reflectance of human skin and printed skin color are different.
4.5 Conclusion

In this chapter, skin color images are reproduced colorimetrically on hardcopy under various illuminants. The averaged color difference of 4.9 between the measured and predicted tristimulus values shows sufficient accuracy of the proposed colorimetric color reproduction.

It is noticed that the color reproduction of portrait on CRT is different from the hardcopy under various illuminants because the chromatic adaptation is not considered yet in the reproduction on CRT.

The color reproduction described in this paper is not applicable to the lips, hair, eyes and so on, because only the spectral reflectance of human skin was considered here.

**Figure 17.** Comparison between averaged spectral reflectance of human skin and printed skin color.
5.1 Introduction

Experimental methods to predict the tristimulus values of skin color under various illuminants on CRT and hardcopy were described in Chapters 3 and 4. In this chapter a method of color reproduction based on color appearance models is described. This reproduction can be made matching the appearance of CRT with the reproduction on hardcopy under various illuminants.

Some color appearance models are introduced in the colorimetric color reproduction on CRT. However, there is not a standard color appearance model to match the skin color appearance. Then, a comparison between color appearance models is required to select a suitable model for skin color appearance reproduction. In this chapter an outline of some color appearance models and viewing techniques for psychophysical experiments are also presented.

5.1.1 Chromatic adaptation models

A) von Kries model

The von Kries coefficient law is based on the complete adaptation of human color visual system to the white point of the illuminant. The cone fundamental tristimulus values \( L, M, S \) are simply multipliclated 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 at new adapting field, $L_a$, $M_a$, and $S_a$ can be written as follows:

$$L_a = k_L L, \quad k_L = \frac{L_{Na}}{L_{No}},$$

(5-1a)

$$M_a = k_M M, \quad k_M = \frac{M_{Na}}{M_{No}},$$

(5-1b)

$$S_a = k_S S, \quad k_S = \frac{S_{Na}}{S_{No}},$$

(5-1c)

where, $L$, $M$, and $S$ are the excitations of cones on retina at original adapting field, $k_L$, $k_M$, and $k_S$ are multiplicative factors, $L_{Na}$, $M_{Na}$, and $S_{Na}$ are cone excitations for the white point of new adapting illuminant, and $L_{No}$, $M_{No}$, and $S_{No}$ are the cone excitations for the white point of original illuminant.

B) CIELAB (LAB) color space

In 1976, CIE recommended CIELAB color space 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. (5-2),

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

(5-2a)

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

(5-2b)

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

(5-2c)

where $X_N$, $Y_N$, and $Z_N$ are the tristimulus values of the illumination white point.
The tristimulus values $X_a$, $Y_a$, $Z_a$ at the new adapting field can be calculated as follows:

$$X_a = \left( \frac{a^*}{500} + \left( \frac{L^* + 16}{116} \right) \right)^3 X'_N, \quad (5-3a)$$

$$Y_a = \left( \frac{L^* + 16}{116} \right)^3 Y'_N, \quad (5-3b)$$

$$Z_a = \left( \frac{L^* + 16}{116} - \frac{b^*}{200} \right)^3 Z'_N, \quad (5-3c)$$

where $X'_N$, $Y'_N$, and $Z'_N$ are the tristimulus values of the white point of the adapting illuminant. CIELAB was not standardized to be a color appearance model. However it provides a good approximation for color appearance in near-daylight conditions.

C) Fairchild color appearance model

The Fairchild color appearance model uses incomplete chromatic adaptation of cones to the white point. This model is based on von Kries coefficient law, with an introduction of a functional expression proposed by Hunt\textsuperscript{46} for incomplete levels of adaptation as shown in Eq. (5-4).

$$L' = \rho_L \frac{L}{L_N}, \quad (5-4a)$$

$$M' = \rho_M \frac{M}{M_N}, \quad (5-4b)$$

$$S' = \rho_S \frac{S}{S_N}, \quad (5-4c)$$

where $L'$, $M'$, and $S'$ are the cone excitations considering a certain degree of chromatic adaptation. $\rho_L$, $\rho_M$, and $\rho_S$ 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 (5-4) can be expressed in matrix form as shown in Eq. 
(5-5).

\[
\begin{bmatrix}
L' \\
M' \\
S'
\end{bmatrix} = \mathbf{A}
\begin{bmatrix}
L \\
M \\
S
\end{bmatrix},
\]

(5-5)

The matrix \(\mathbf{A}\) is

\[
\begin{bmatrix}
a_L & 0 & 0 \\
0 & a_M & 0 \\
0 & 0 & a_S
\end{bmatrix},
\]

(5-6)

where

\[
a_L = \rho_L/L_N, \quad (5-7a)
\]

\[
a_M = \rho_M/M_N, \quad (5-7b)
\]

\[
a_S = \rho_S/S_N. \quad (5-7c)
\]

The degree of chromatic adaptation can be calculated as follows:

\[
\rho_L = \frac{1 + Y_N^\nu + \ell_E}{(1 + Y_N^\nu + 1/\ell_E)}, \quad (5-8a)
\]

\[
\rho_M = \frac{1 + Y_N^\nu + m_E}{(1 + Y_N^\nu + 1/m_E)}, \quad (5-8b)
\]

\[
\rho_S = \frac{1 + Y_N^\nu + s_E}{(1 + Y_N^\nu + 1/s_E)}, \quad (5-8c)
\]

where \(Y_N\) is the luminance of the illuminant, \(\nu\) is an exponent that defines the shape of
the degree of the adaptation function and \(\ell_E, m_E,\) and \(s_E\) are the fundamental
chromaticity coordinates of the adapting stimulus. Originally, Fairchild used the
exponent \(\nu\) equal to 0.22 as suggested for a dark environment. This exponent value
was set equal to 0.29 in the refinement of RLAB model by Fairchild.\textsuperscript{72} The $\ell_E$, $m_E$, and $s_E$ values are calculated as follows:

$$\ell_E = \frac{3L_N}{L_N + M_N + S_N},$$

(5-9a)

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

(5-9b)

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

(5-9c)

From the Eqs. (5-4) to (5-9), we can see that the adaptation will be less complete for increasing values of the saturation of the adapting stimulus. The equations above also show that the adaptation will be more complete for increasing values of the luminance of the adapting stimulus.

The final step in the calculation of adaptation cone signals is a transformation considering interaction among cones given by Eq. (5-10). This transformation allows the model to predict increases of the perceived colorfulness called Hunt effect. This transformation also allows the prediction of the increases of contrast with increasing luminance, called Stevens effect.\textsuperscript{108}

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

(5-10)

where $c$ is calculated as follows:

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

(5-11)

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,
\[
\begin{bmatrix}
X_A \\
Y_A \\
Z_A
\end{bmatrix} = M^{-1}A_2^{-1}C_2^{-1}C_1A_1M \begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}, \quad (5-12)
\]

where matrix \( M \) is the transformation from tristimulus values to cone fundamental primaries. Matrix \( A_1 \) and \( C_1 \) respectively the matrices of Eqs. (5-6) and (5-10) for adapting condition 1. Matrix \( A_2 \) and \( C_2 \) are respectively the matrices of Eqs. (5-6) and (5-10) for adapting condition 2.

Fairchild and Berns incorporate this chromatic adaptation model into CIE 1976 (\( L^*, a^*, b^* \)) color space in the RLAB color appearance model.\(^{38}\) This color space can determine the required colors for reproduction across changes in media and viewing conditions. This model can also be used for calculating metrics of lightness, chroma, hue and color difference.

D) LLAB color appearance model.

In the model proposed by Luo and coworkers,\(^{73,74}\) the \( R_r, G_r, B_r \) cone responses at new adapting field is calculated from the \( R_s, G_s, B_s \) cone at original adapting field using the following equations:

\[
R_r = \left[ D \left( \frac{R_r}{R_{os}} \right) + 1 - D \right] R_s, \quad (5-13a)
\]

\[
G_r = \left[ D \left( \frac{G_r}{G_{os}} \right) + 1 - D \right] G_s, \quad (5-13b)
\]

\[
B_r = \left[ D \left( \frac{B_r}{B_{os}} \right) + 1 - D \right] B_s^\beta, \quad \text{for } B_s \geq 0 \quad (5-13c)
\]

\[
B_r = -\left[ D \left( \frac{B_r}{B_{os}} \right) + 1 - D \right] B_s^\beta, \quad \text{for } B_s < 0 \quad (5-13d)
\]
where $\beta = \left( \frac{B_{or}}{B_{os}} \right)^{0.0834}$, $R_{os}$, $G_{os}$, $B_{os}$ are the cone responses for the white point under original adapting field; $R_{or}$, $G_{or}$, $B_{or}$ are the cone responses for the white point in the environment in which the image will be reproduced; $D$ value is 1.0 for hardcopies and 0.7 for CRT in dim surround.

5.1.2 Viewing techniques for cross-media comparison

The comparison of color appearance models is based on the recommendations of many technical committees such as CIE Technical Committee 1-34, “Testing Colour-Appearance Models in order to establish standard guideline for coordinated research on evaluation of color appearance models for hardcopy and image on CRT”. The recommended methods use psychophysical experiments to select a suitable color appearance model for cross-media reproduction. The psychophysical experiments for the comparison of color appearance models are based on many viewing techniques such as successive-binocular, simultaneous-binocular, simultaneous-haploscopic, successive-Ganzfeld haploscopic, and memory matching technique. In the memory matching technique, the illumination booth with the hardcopy and the CRT are placed at 90 degrees from each other ensuring that observers can not see both images on CRT and the hardcopy at the same time. In this technique observers are asked to observe the image in the booth before observing the image on CRT to compare images under different conditions. In this technique observers are allowed to look at both hardcopy and CRT only once. The successive-binocular viewing is equal to the memory technique except that observers are allowed to look at both hardcopy and CRT as much time as necessary to compare images. In the simultaneous-binocular technique, the hardcopy in the illumination booth and the image on CRT are place side by side and the observer is instructed to see the hardcopy and image on CRT with both eyes. In the
simultaneous-haploscopic technique observers are instructed to observe the hardcopy with one eye and the image on CRT with the other eye. This technique allows that each eye adapts to a different white point while comparing the images. The successive-Ganzfeld haploscopic viewing technique is similar to the simultaneous-haploscopic viewing technique except that observers are not allowed to view both the hardcopy and image on CRT at the same time. In this technique covers with a neutral field switches over each eye allowing adaptation while the other eye is observing the image.

These viewing techniques have been compared by psychophysical methodology such as the experiments performed by Braun and Fairchild. The binocular matching was more preferred than haploscopic matching. It happens because the binocular viewing is more natural way of viewing, and it is easier (it is accomplished without the necessity of any special device) and more comfortable for the observer than haploscopic viewing. These experiments also show that a successive color viewing was preferred than a simultaneous color viewing because successive matching yielded the shorter matching times and interocular interactions can be controlled. Based on the considerations above, the memory matching that combines easiness, successive color matching and binocular color matching is preferred than other viewing techniques to compare reproduced images using various color appearance models. Therefore, memory matching technique will be used in the psychophysical experiments.

5.2 Color appearance matching method

Figure 18 shows a schematic diagram of the skin color reproduction method based on color appearance model. 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 $X'$, $Y'$, $Z'$ obtained by colorimetric color reproduction. At first, $X'$, $Y'$, $Z'$ are transformed to cone fundamental tristimulus values $L$, $M$, and $S$. The Hunt-Pointer-
Estévez transformation are used to calculate $L$, $M$, $S$ values, as shown in Eqs. (5-14) and (5-15). This transformation is normalized to CIE Illuminant D65.

\[
\begin{bmatrix}
L \\
M \\
S
\end{bmatrix}
= \begin{bmatrix}
X' \\
Y' \\
Z'
\end{bmatrix}
\]

\[
E(\lambda) \rightarrow O(\lambda) \rightarrow M \rightarrow (X', Y', Z') \rightarrow \text{Color appearance models} \rightarrow (L_a, M_a, S_a) \rightarrow M^{-1} \rightarrow (X_a, Y_a, Z_a) \rightarrow \text{Color Transform Matrix} \rightarrow \text{CRT display}
\]

\[
\begin{bmatrix}
L \\
M \\
S
\end{bmatrix} = \begin{bmatrix}
0.40 & 0.71 & -0.08 \\
-0.23 & 1.17 & 0.05 \\
0.00 & 0.00 & 0.92
\end{bmatrix} \begin{bmatrix}
X' \\
Y' \\
Z'
\end{bmatrix}
\]

Figure 18. Diagram of color reproduction of facial pattern images on CRT based on color appearance models.
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 using color appearance models. The predicted values $L_a$, $M_a$, and $S_a$ were calculated using von Kries, and Fairchild models. Next, $X_a$, $Y_a$, and $Z_a$ considering chromatic adaptation are calculated by the inverse of matrix $M$. Finally, the predicted tristimulus values $X_a$, $Y_a$, and $Z_a$ are reproduced on CRT using color transform matrix.

5.3 Psychophysical experiments

Psychophysical experiments were performed to select a suitable color appearance model for the reproduction of skin color images on CRT in a dark environment. The images on CRT were compared with a hardcopy illuminated in a standard illumination booth (Macbeth Spectralight II). The booth contains four illuminants; “Horizon”, “A”, “Cool White”, and “Day Light”. The spectral radiances of these illuminants are shown in Fig. 11. We reproduced five facial pattern images of a Japanese woman and six skin color patches. The chromaticities of skin color patches are extracted from the facial pattern images and the tristimulus values of the six color patches under “A” illuminant are shown in Table 6.
Table 6. The tristimulus values of the six skin color patches under illuminant “A”.

<table>
<thead>
<tr>
<th>Patch</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>105</td>
<td>90</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>72</td>
<td>66</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>75</td>
<td>70</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>38</td>
<td>37</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>47</td>
<td>45</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>72</td>
<td>61</td>
<td>14</td>
</tr>
</tbody>
</table>

Four images were generated on CRT for each illuminant; an image generated by $X'$, $Y'$ and $Z'$ without considering chromatic adaptation, named $XYZ$ image; an image generated by von Kries color appearance model, von Kries image; an image generated by Fairchild model, Fairchild image; and an image generated by CIELAB model, CIELAB image. Figure 19 shows an example of predicted color appearance for the skin color patches under various illuminants. The reproduction for each color appearance model is shown in Figs. 20, 21, 22 and 23 respectively, under illuminant “A”, “Horizon”, “Cool white”, and “Day Light”.
Figure 19. Predicted color appearance of skin color patches under various illuminants; (a) illuminant “A”, (b) “Horizon”, (c) “Cool White”, (d) “Day Light”.

Chapter 5
Figure 20. Color appearance predictions of a facial pattern image under illuminant “A”; (a) XYZ, (b) CIELAB, (c) von Kries, (d) Fairchild.
Figure 21. Color appearance predictions of a facial pattern image under “Horizon”; (a) XYZ, (b) CIELAB, (c) von Kries, (d) Fairchild.
Figure 22. Color appearance predictions of a facial pattern image under “Cool White”; (a) XYZ, (b) CIELAB, (c) von Kries, (d) Fairchild.
Figure 23. Color appearance predictions of a facial pattern image under “Day Light”; (a) XYZ, (b) CIELAB, (c) von Kries, (d) Fairchild.
Figure 24 shows a viewing technique using memory matching that was used to select a suitable color appearance model to reproduce skin color images on CRT.

**Figure 24.** Arrangement of psychophysical experiment to compare skin color images on a CRT with a hardcopy in a standard illumination booth using memory matching.

Both CRT and hardcopy were arranged at an equal viewing distance of approximately 1 m from the observer. The images, whether it is on the CRT or in the illumination booth, would be observed with both eyes. The observer can see the CRT and the hardcopy only once to obtain a comparative judgment.
Ten observers took part in this experiment. They 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 a minute. You will be asked to memorize the skin color of the image. Turn towards the CRT, 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 observers were asked to look the image for about one minute because Fairchild and Reniff found that chromatic adaptation at constant luminance was 90% complete after approximately 60 seconds. The position of each model on the CRT was randomized for each set of predicted images.

5.4 Experimental results

Figure 25 shows the percentage of skin color patch that was selected as the best one in 4 kinds of models on CRT. Figure 25(a) shows the percentage of selection under various illuminants. From Fig. 25(a), we can see that the color appearance of patch by Fairchild model was chosen as the best one. Figure 25(b) shows the percentage of selection for each illuminant. It is possible to observe that the incomplete adaptation, Fairchild model, was effective under “Horizon”, “Cool White” and illuminant “A”. However, under “Day Light”, Fairchild model was selected as well as the model proposed by von Kries.
Figure 25. Percentage of selection of each color appearance model for skin color patch reproduction.

On the other hand, Fig. 26 shows the percentage of selection of each color appearance model for reproduced facial pattern image. Figure 26(a) shows the percentage of selected models under various illuminants. It is clear that Fairchild model
was chosen as well as the color patches. Figure 26(b) shows the percentage of selected model for each illuminant.

![Bar Chart](image)

(a) Selected model under various illuminants.

![Bar Chart](image)

(b) Selected model under each illuminant.

**Figure 26.** Percentage of selection of each color appearance model for facial pattern image reproduction.
It is clear that, there is no significant difference among illuminants for each model for facial pattern images.

The comparison of the results obtained in Figs. 25 and 26 shows that the performance of Fairchild model was not so good for facial pattern images as in the case of skin color patches. The model proposed by Fairchild was applied well to skin color patches but it was not effective for facial pattern images as skin color patches. Facial skin color is one of the human memorized colors. We can believe that this difference in the performance of Fairchild model is due to the memorized colors\(^\text{118}\).

### 5.5 Conclusion

A color reproduction method based on color appearance models was used to match the appearance of skin color on CRT with hardcopy under various illuminants. The colorimetric color reproduction was compared with images reproduced using color appearance models proposed by von Kries, Fairchild and CIELAB color space. The results of psychophysical experiments using memory matching showed that the incomplete chromatic adaptation model proposed by Fairchild is a better model than CIELAB or von Kries. It confirms that an incomplete chromatic adaptation model is effective for complex image.\(^\text{119}\) However, the model proposed by Fairchild does not be applied to facial pattern image as well as skin color patches. These results show that more studies of the influence of memorized facial skin color are necessary.

The effect of surround on CRT\(^\text{120}\) and the effect of individual variation of color matching functions\(^\text{121,122}\) could also be applied to skin color reproduction.
CHAPTER 6

MODIFIED FAIRCHILD CHROMATIC ADAPTATION MODEL
FOR FACIAL PATTERN IMAGES

6.1. Introduction

The incomplete chromatic adaptation model proposed by Fairchild could be applied well
for skin color patches as shown in a previous chapter. However this model could not
apply to facial pattern image as well as for skin color patches. Therefore, I tried to
modify Fairchild model for facial pattern images.

6.2. Modified Fairchild chromatic adaptation model

Coefficients $K_L, K_M, K_S$, were introduced in Eq. (5-9) as follows,

\[ \ell_E = \frac{K_L L_N}{L_N + M_N + S_N}, \]  
\[ m_E = \frac{K_M M_N}{L_N + M_N + S_N}, \]  
\[ s_E = \frac{K_S S_N}{L_N + M_N + S_N}. \]  

In the Fairchild model, the coefficients $K_L, K_M, K_S$ are defined as 3.0. These color
coefficients provide adjustment of the degree of color balance for facial pattern images.
6.3. Psychophysical experiments to tune color balance.

Psychophysical experiments using memory matching were performed to select the optimum coefficients of color balance for facial pattern image. The coefficients $K_L$, $K_M$, $K_S$ were varied from 2.9 to 3.2 in intervals of 0.1 unit. These 64 combinations of coefficients were used to reproduce a facial pattern image under three kinds of illuminants (“A”, “Day Light”, “Cool White”). The observer was asked to select on CRT the most similar image to the original hardcopy using memory matching as described in Chapter 5. The results of this experiment were shown in Figs. 27(a), (b), (c), and (d).

Figure 27(a). A number of selection when $K_M$, $K_S$ are changed from 2.9 to 3.2 and $K_L = 2.9$. 
Figure 27(b). A number of selection when $K_M$, $K_S$ are changed from 2.9 to 3.2 and $K_L = 3.0$.

Figure 27(c). A number of selection when $K_M$, $K_S$ are changed from 2.9 to 3.2 and $K_L = 3.1$. 
6.4. Comparison of the modified Fairchild model with other color appearance models.

A) Experiment A (Modified Fairchild, XYZ, von Kries, Fairchild)

The coefficients of color balance in the modified Fairchild incomplete chromatic adaptation equations were set as $K_L = 3.1$, $K_M = 2.9$, $K_S = 3.1$ and the performance of this modified model was compared with colorimetric color reproduction and other color appearance models (von Kries, Fairchild) by psychophysical experiments. The reproduced images under illuminant “A” are shown in Fig. 28.
Figure 28. A facial pattern image reproduced on a CRT for illuminant “A”; (a) XYZ, (b) Modified Fairchild (Custom model), (c) von Kries, (d) Fairchild.

Psychophysical experiments were performed using memory matching. A hardcopy in a standard illuminant booth was compared with a pair of reproductions on CRT in a dark environment. Ten observers were asked to select the reproduction on CRT that provides the best match in color appearance with the hardcopy. The choices of reproduction on CRT were converted to an interval scale of color reproduction quality for various models using Thurstone’s law of comparative judgments\textsuperscript{123}. Using statistical procedures described by Torgeson\textsuperscript{124} the averaged z-scores for each model were calculated. These z-scores give interval scale values of each model indicating their
performance in the reproduction of the original hardcopy. A confidence interval of 95% for the averaged value is calculated in Eq. (6-2).

\[ \pm 1.96 \frac{0.707}{\sqrt{N} \sqrt{M}} , \]  

(6-2)

where \( N \) is the number of observation for a sample, \( M \) is the number of tested models. In our experiment, the confidence interval around each scale value was 0.283, where \( N=15 \) and \( M=4 \). The performances of two models are considered as equivalent if the average of one model falls within the error bar of another model. The results of these experiments are shown in Figs. 29(a), (b), and (c), where “Custom” indicates the modified Fairchild model for facial pattern image. The central bar in each plot of Figs. 29(a), (b), and (c) indicate the averaged interval scale value and the bars indicate the error in 95% confidence interval. In the case of the XYZ image under “Day Light” illuminant it was not possible to calculate the z-score because XYZ reproduction was not selected at all.

![Figure 29(a). Averaged interval scale of model performance for illuminant “A”.](image-url)
The statistical result of these comparisons showed that the modified Fairchild model (Custom model) had the best averaged z-scores for all kind of illuminants. The XYZ image showed the worst results because this reproduction does not consider chromatic adaptation.
B) Experiment B (Modified Fairchild, von Kries, RLAB 96, LLAB)

XYZ and Fairchild reproductions were replaced by the RLAB refinement published in 1996 (RLAB 96), 72 and LLAB model 73, 74 to refine and update the psychophysical experiments. These models were tested for both skin color patches and facial pattern images. Figure 30 shows a reproduced skin color patch under illuminant “A”. Figure 31 shows the reproduced facial pattern image under illuminant “A”.

![Skin Color Patch Images](image)

(a) RLAB 96  
(b) Custom  
(c) von Kries  
(d) LLAB

**Figure 30.** A skin color patch reproduced on CRT display for illuminant “A”; (a) RLAB 96, (b) Modified Fairchild (Custom model), (c) von Kries, (d) LLAB models.
Figure 31. A facial pattern image reproduced on CRT display for illuminant “A”; (a) RLAB 96, (b) Modified Fairchild (Custom), (c) von Kries, (d) LLAB models.
Six color patches were examined by two observers and a facial pattern image was observed by ten observers. Figure 32 shows the percentage of skin color patch that was selected on CRT as the best one in 3 kind of illuminants. On the other hand, Fig. 33 shows the percentage of selection for the facial pattern image chosen as the best one on CRT display in 3 kind of illuminants.

**Figure 32.** Percentage of skin color patch that was selected on CRT as the best one in 3 kind of illuminants.
Figure 33. Percentage of selection for reproduced facial pattern image chosen as the best one on CRT display in 3 kind of illuminants.

From Fig. 32, it is clear that the color appearance of patch by RLAB 96 model was chosen as the best one. In this case the modified Fairchild model did not perform well as RLAB 96 model because the coefficients of color balance were adjusted for facial pattern image and not for skin color patches. From Fig. 33 it is possible to see that LLAB model performed well for illuminant “A” but it could not predict well other illuminants used in the experiment. On the other hand, von Kries model performed well for “Day Light” and “Cool White” but it presented poor results for illuminant “A”. RLAB 96 model performed relatively well, however the modified Fairchild model (Custom model) presented the overall best result under all kind of illuminants.

The result was also analyzed statistically. Figures 34(a), (b), and (c) show the averaged interval scale values for each reproduced facial pattern image under various illuminants.
Figure 34(a). Averaged interval scale of model performance for illuminant “A”.

Figure 34(b). Averaged interval scale of model performance for “Day Light”.

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From Figs. 34(a) and (b) it is clear that von Kries and RLAB 96 models are approximately same in statistical values for facial pattern image reproduction under “A” and “Day Light” illuminants. From Fig. 34(c) it can be also found that von Kries and LLAB models are approximately same in statistical values for reproduction under “Cool white” illuminant. It is also possible to see from Fig. 34(c) that RLAB 96 and Custom models are approximately same in statistical values for reproduction under “Cool white” illuminant.

6.5. Conclusion

It was found from the psychophysical experiments that the performance of color appearance models for facial pattern depends on the illuminant. The modified Fairchild color appearance model (custom model) performed well for facial pattern images and showed the best averaged z-scores for all kind of illuminants. We can conclude that the proposed modified Fairchild model can be performed well to reproduce facial pattern images.
Chapter 7

COLOR REPRODUCTION OF ENDOSCOPIC IMAGES UNDER ENVIRONMENTAL ILLUMINATION

7.1 Introduction

In recent years, electronic endoscope has been widely used for diagnosis of various kinds of diseases. The color of stomach and intestine mucosa gives significant information for diagnosis of many diseases such as gastritis, cancer and so on. Sometimes the physician needs to ask another specialist for the diagnosis. The process of sending and receiving images from one hospital to another has been possible with the advance of telecommunication systems. However, in these systems the viewing conditions and devices vary case-by-case. Then, it is necessary to consider the influence of the environmental conditions on the appearance of reproduced image. The endoscopic images are generally viewed by physician in dark environment of an operation room. However, when the images are viewed in another room, such as meeting room, it is necessary to consider the influence of environmental illuminant on the appearance of endoscopic images. It is necessary to do gamut-mapping for image which cannot be reproduced in the gamut of CRT. However, there is not any way to quantify how gamut-mapping affects the perceived color appearance.

In this chapter, a perceptual color difference is defined to evaluate gamut-mapping for endoscopic image reproduced on CRT under environmental illumination instead of the traditional color difference. The perceptual color difference is defined by Mahalanobis distance which is calculated using the covariance matrix of metric lightness, chroma and hue angle.
7.2 Color reproduction method for endoscopic images under environmental illumination

Figure 35 shows a schematic diagram of a color reproduction method to reproduce the appearance of endoscopic images on CRT under various illuminants.

**Figure 35.** Diagram of color reproduction method to reproduce the appearance of endoscopic images on CRT under various illuminants.
In Fig. 35, the R, G, B original endoscopic image is transformed to X, Y, Z using the characteristics of the CRT in the dark environment. The color appearance is calculated from X, Y, Z values and represented in CIELUV L*, C*, and h values. The gamut-mapping was performed to adjust the L*, C*, h values on CRT 1 to the L*', C*', h' values on CRT 2 under various illuminants. The inverse chromatic adaptation is performed to get X’, Y’, Z’. The X, Y, Z tristimulus values of the reflected light on CRT surface are subtracted from X’, Y’, Z’ to give X”, Y”, Z” tristimulus values of emitted light on CRT surface. Finally, the X”, Y”, Z” was transformed to the device dependent R’, G’, B’ that are displayed on CRT. X, Y, Z can be calculated from the spectral reflectance of the CRT surface ρ(λ) using the following equations:

\[
X_L = K \int_{400}^{700} E(\lambda) \rho(\lambda) \bar{x}(\lambda) d\lambda, \tag{7-1a}
\]

\[
Y_L = K \int_{400}^{700} E(\lambda) \rho(\lambda) \bar{y}(\lambda) d\lambda, \tag{7-1b}
\]

\[
Z_L = K \int_{400}^{700} E(\lambda) \rho(\lambda) \bar{z}(\lambda) d\lambda, \tag{7-1c}
\]

\[
K = 100/ \int_{400}^{700} E(\lambda) \bar{y}(\lambda) d\lambda, \tag{7-1d}
\]

where E(λ) is the spectral radiance of the illuminant.

The measurement of spectral reflectance ρ(λ) of the CRT depends on the viewing angle, so it was assumed that the endoscopic images are displayed on the center of the CRT and the observer watched the images in a fixed position in front of the CRT. The spectral reflectance ρ(λ) of the CRT was obtained dividing the amount of radiant power reflected on CRT by the amount of radiant power reflected on the white perfect diffuser. The amounts of radiant power of three illuminants (“A”, “Cool white” and “Day Light” whose relative spectral radiances are given in Fig. 11) were measured on a
white diffuser with reflectance of approximately 90%. Eventual scattering of light inside the CRT was ignored. The spectral reflectance was calculated for three kinds of illuminants to examine the illuminant dependence of the spectral reflectance as shown in Figs. 36(a), (b) and (c), respectively under “A”, “Cool white” and “Day Light.” As expected, the spectral reflectance has approximately the same shape for these three kinds of illuminants.

**Figure 36(a).** Spectral reflectance of CRT without radiation from CRT under illuminant “A”.

![Spectral reflectance graph](image-url)
Figure 36(b). Spectral reflectance of CRT without radiation from CRT under “Cool White”.

Figure 36(c). Spectral reflectance of CRT without radiation from CRT under “Day Light”.

$X_L$, $Y_L$, $Z_L$ were calculated using spectral reflectance $\rho(\lambda)$ for each illuminant and the values are shown in the Table 7.
Table 7. $X_L$, $Y_L$, $Z_L$ tristimulus values of reflected light on CRT under various illuminants.

<table>
<thead>
<tr>
<th>Illuminant</th>
<th>Illuminant “A”</th>
<th>“Cool White”</th>
<th>“Day Light”</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_L$</td>
<td>6.24</td>
<td>5.84</td>
<td>1.88</td>
</tr>
<tr>
<td>$Y_L$</td>
<td>5.52</td>
<td>5.83</td>
<td>2.95</td>
</tr>
<tr>
<td>$Z_L$</td>
<td>3.68</td>
<td>4.07</td>
<td>4.24</td>
</tr>
</tbody>
</table>

The incomplete chromatic adaptation model proposed by Fairchild was used to predict the color appearance as in the case of skin color. The chromatic adaptation on CRT in a dark environment occurs in relation to the white point of the CRT. In the case of illuminated CRT, Katoh considered mixed chromatic adaptation.\textsuperscript{10,11,125} Katoh found that human visual system is 60% adapted to CRT white point and 40% to the ambient light. However, as Katoh stated, the degree of adaptation depends on the time of observation and the distance from the CRT. In medical systems, it is difficult to reproduce the same experimental conditions used by Katoh. Then, it is assumed that chromatic adaptation occurs to the white point of CRT added to the tristimulus values of reflected light on CRT. The color reproduction of the tristimulus values $X'$, $Y'$, $Z'$ of CRT under illumination could be predicted from the $X$, $Y$, $Z$ of the CRT in the dark environment using a simple linear transformation of multiplying matrices as shown in Eq. (7-2), which was rewritten from Eq. (5-12).

$$
\begin{bmatrix}
X' \\
Y' \\
Z'
\end{bmatrix}
= M^{-1}A_2^{-1}C_2^{-1}C_1A_1M 
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix},
$$

(7-2)
7.3 Gamut-mapping of endoscopic image

7.3.1 Gamut-mapping in 1976 CIELUV L*C*h color space

The objective of gamut-mapping is to find a way to display the processed colors that are out of color gamut in CRT. The gamut-mapping should ensure that the appearance of the reproduction is as close to the original as possible. This appearance fidelity of the reproduced image to the original is very important in remote diagnosis for endoscopic images, because diagnosis of physicians is mainly based on the appearance of color.

The \( L_{uv}^* \), \( C_{uv}^* \), \( h_{uv} \) metric lightness, chroma, and hue angle respectively were used for gamut-mapping because these color attributes have a psychophysical meaning. The relationship between the tristimulus values and the \( L^*, u^*, v^* \) are given by Eq. (7-3) and the relationship between \( L^*, u^*, v^* \) and \( L_{uv}^*, C_{uv}^*, h_{uv} \) is shown in Fig. 37.

\[
L^* = 116 \left( \frac{Y}{Y_n} \right)^{\frac{1}{3}} - 16 \quad \text{for} \quad \frac{Y}{Y_n} > 0.008856, \quad (7-3a)
\]
\[
L^* = 903.3 \frac{Y}{Y_n} \quad \text{for} \quad \frac{Y}{Y_n} \leq 0.008856, \quad (7-3b)
\]
\[
C_{uv}^* = \sqrt{(u^*)^2 + (v^*)^2}, \quad (7-3c)
\]
\[
h_{uv} = \tan^{-1}\left( \frac{u^*}{v^*} \right), \quad (7-3d)
\]

where

\[
u^* = 13L'(u' - u'_{n'}), \quad (7-3e)
\]
\[
v^* = 13L'(v' - v'_{n'}), \quad (7-3f)
\]
\[
u' = \frac{4X}{X + 15Y + 3Z}, \quad (7-3g)
\]
\[
u'_{n'} = \frac{4X_n}{X_n + 15Y_n + 3Z_n}, \quad (7-3h)
\]
\[
\frac{9Y}{X + 15Y + 3Z}, \quad (7-3i)
\]
7.3.2 Perceptual Mahalanobis distance

The gamut-mapping algorithms are evaluated using psychophysical techniques, as performed by Katoh\textsuperscript{126,127} considering differences in metric lightness ($\Delta L$), chroma ($\Delta C$), and hue angle ($\Delta h$). However, the weighted color difference $\Delta E$ which was proposed by Katoh, as shown in Eq. (7-4), does not consider the correlation between the lightness, chroma and hue angle.

\[
\Delta E = \left[ \left( \frac{\Delta L^*}{K_l} \right)^2 + \left( \frac{\Delta C^*_{ab}}{K_c} \right)^2 + \left( \frac{\Delta H^*_{ab}}{K_h} \right)^2 \right]^{1/2},
\]

where $\Delta L^*$, $\Delta C^*_{ab}$, $\Delta H^*_{ab}$ are differences in lightness, chroma, and hue respectively. $K_l$, $K_c$, $K_h$ are mapping coefficients for each attribute of color.
The CIE 1994 total color-difference\textsuperscript{128} shown in Eq. (7-5) uses correlation between hue and chroma in the estimation of weighting functions. However, it does not consider the correlations between lightness and hue, lightness and chroma.

\[
\Delta E_{94}^* = \left( \frac{\Delta L}{k_L S_L} \right)^2 + \left( \frac{\Delta C_{ab}^*}{k_C S_C} \right)^2 + \left( \frac{\Delta H_{ab}^*}{k_H S_H} \right)^2 \]  \tag{7-5}
\]

where \( k_L, k_C, k_H \) are parametric factors, \( S_L, S_C, S_H \) are weighting functions. \( S_L = 1; S_C = 1 + 0.045 C_{ab}^*; S_H = 1 + 0.015 C_{ab}^* \) are currently recommended by CIE.

A perceptual color distance based on Mahalanobis distance is defined using covariance matrix of perceptually equivalent metric lightness, chroma and hue angle of endoscopic images. The Mahalanobis distance\textsuperscript{129} makes uniform the influence of the distribution of each attribute and is defined as follows:

\[
d = \left\{ \begin{array}{c}
\Delta L \\
\Delta C \\
\Delta h \\
\end{array} \right\} \begin{bmatrix}
V_{LL} & V_{LC} & V_{Lh} \\
V_{LC} & V_{CC} & V_{Ch} \\
V_{Lh} & V_{Ch} & V_{hh}
\end{bmatrix}^{-1} \begin{bmatrix}
\Delta L \\
\Delta C \\
\Delta h \\
\end{bmatrix} \right\}^{1/2}, \tag{7-6}
\]

where \( V_{LL}, V_{CC}, V_{hh} \) are the variances of metric lightness, chroma, hue angle, respectively. On the other hand, \( V_{LC}, V_{Lh}, V_{Ch}, V_{hh} \) are the covariances between metric lightness and chroma, lightness and hue angle, and chroma and hue angle, respectively. This perceptual distance can be used to evaluate gamut-mapping. The gamut-mapping that provides the shortest perceptual Mahalanobis distance is considered as the best reproduction.
7.3.3 Psychophysical experiments

Psychophysical experiments were performed to find a covariance matrix to define the Mahalanobis distance for endoscopic image. For this purpose, the lightness of endoscopic image was changed by -4, -2, 0, 2, 4 units, the chroma was changed by -6, -3, 0, 3, 6 units, and the hue angle was changed by -2, -1, 0, 1, 2 degrees depart from the original image. Every possible combination of these three color attributes was prepared as 125 sets of endoscopic images. Each image was displayed randomly. Ten observers who are students and staff of our laboratory were asked to watch each pair on CRT and they were asked to select if two images are the same or not. The statistical result of this experiment is shown in Table 8.

Table 8. Variances and covariances for metric lightness, chroma and hue angle of endoscopic image.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance of metric lightness</td>
<td>$V_{LL}$</td>
<td>5.818</td>
</tr>
<tr>
<td>Variance of metric chroma</td>
<td>$V_{CC}$</td>
<td>11.29</td>
</tr>
<tr>
<td>Variance of metric hue angle</td>
<td>$V_{hh}$</td>
<td>1.326</td>
</tr>
<tr>
<td>Covariance between metric lightness and chroma</td>
<td>$V_{LC}(V_{CL})$</td>
<td>2.664</td>
</tr>
<tr>
<td>Covariance between metric lightness and hue angle</td>
<td>$V_{Lh}(V_{hl})$</td>
<td>0.2198</td>
</tr>
<tr>
<td>Covariance between metric chroma and hue angle</td>
<td>$V_{Ch}(V_{hc})$</td>
<td>-1.544</td>
</tr>
</tbody>
</table>

From Table 8, the variance of chroma is greater than variance of lightness; and then the variance of lightness greater than variance of hue angle.
The perceptual Mahalanobis distance can be calculated by Eq. (7-7),

$$d = \left\{ \begin{bmatrix} \Delta L & \Delta C & \Delta h \end{bmatrix} \begin{bmatrix} 0.2047 & -0.0630 & -0.1071 \\ -0.0630 & 0.1247 & 0.1556 \\ -0.1071 & 0.1556 & 0.9530 \end{bmatrix} \begin{bmatrix} \Delta L \\ \Delta C \\ \Delta h \end{bmatrix} \right\}^{\frac{1}{2}}.$$ (7-7)

The presence of negative non-diagonal terms in the matrix of Eq. (7-7) is corresponding to the correlation of lightness and chroma, and lightness and hue angle, and it suggests to decrease the perceptual color distance when $\Delta \Gamma \times \Delta \Theta > 0$, where $\Gamma$ and $\Theta$ are $L$, $C$, $h$. On the other way, the positive non-diagonal terms are corresponding to the correlation between metric chroma and hue angle and it indicates to decrease the perceptual color distance when $\Delta \Gamma \times \Delta \Theta < 0$.

Hara and coworkers carried out psychophysical experiment,\textsuperscript{130,131} with collaboration of five physicians. They changed the metric lightness, chroma and hue angle in order to reproduce a preferred endoscopic image on CRT. In this experiment, they only examined variance of metric lightness, chroma, hue angle and covariance between metric chroma and hue angle as shown in Table 9. Unfortunately, it is not possible to calculate the perceptual Mahalanobis distance using the result of Hara’s experiment.
Table 9. Result of psychophysical experiments performed by Hara with the collaboration of physicians.

<table>
<thead>
<tr>
<th>Statistical value of color attribute</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance of metric lightness</td>
<td>$V_{LL}$</td>
<td>23.56</td>
</tr>
<tr>
<td>Variance of metric chroma</td>
<td>$V_{CC}$</td>
<td>34.08</td>
</tr>
<tr>
<td>Variance of metric hue angle</td>
<td>$V_{hh}$</td>
<td>7.44</td>
</tr>
<tr>
<td>Covariance between metric chroma and hue angle</td>
<td>$V_{Ch}(V_{hC})$</td>
<td>-8.97</td>
</tr>
</tbody>
</table>

However, they found that the variance of metric chroma was greater than that of lightness, the variance of lightness was greater than that of hue angle, and covariance between chroma and hue angle have a negative value like the results of the psychophysical experiments shown in Table 8.

7.4 Analysis of gamut-mapping for endoscopic images

Scaling and translation of metric hue angle, chroma and lightness were done for gamut-mapping as shown in Eq. (7-8);

\[
\begin{align*}
    h' &= h + \alpha, \\
    C' &= \beta C + \gamma, \\
    L' &= \phi L + \epsilon,
\end{align*}
\]

where $h$, $C$, $L$ are the hue angle, chroma and lightness respectively before the mapping, the $h'$, $C'$, $L'$ are the mapped hue angle, chroma and lightness respectively, and $\alpha$, $\gamma$, $\beta$, $\epsilon$ and $\phi$ are coefficients of hue angle, chroma translation, chroma scaling, lightness translation, and chroma scaling, respectively. Only one coefficient was used for hue angle since both scaling and translation of hue angle produces rotation of mapped points around lightness axis. The parameters were varied in intervals as described in Table 10.
Table 10. Variation of coefficients $\phi$, $\varepsilon$, $\beta$, $\gamma$, and $\alpha$ in the Eqs. (7-10).

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Initial value</th>
<th>Final value</th>
<th>Interval unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>0.95</td>
<td>1.00</td>
<td>0.05</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>-3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1.0</td>
<td>1.0</td>
<td>0</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>-10</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>-1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

A stomach endoscopic image was reproduced from a CRT (Nanao FlexScan 56T) in a dark environment (corresponding to CRT 1 in Fig. 35) to a CRT (AppleColor High-Resolution RGB Model MO401) under illuminant “A” (CRT 2 in Fig. 35). The characteristics of CRT were described in Chapter 3. Figure 38 shows the endoscopic image to be displayed on a CRT in a dark environment.
Figure 38. Stomach endoscopic image.

This image was chosen because it presents dark and bright regions that are generally difficult to reproduce simultaneously inside the color gamut of the CRT.

Figure 39 shows a reproduction of stomach image shown in Fig. 38 on a CRT under illuminant “A”. This image was not reproduced inside the color gamut of the CRT. In this case 2.76% of the pixels were out of gamut in red channel, 0.86% of pixels were out of gamut in green channel, and however, all pixels were inside the gamut in blue channel. Lightness, chroma and hue angle mapping was applied to the image in Fig. 39 and the perceptual Mahalanobis distance produced by each mapping were calculated when 99% of the pixels are reproduced inside color gamut of the CRT for all the combinations of coefficients $\alpha, \beta, \gamma, \varepsilon$, and $\phi$ changed as shown in Table 10.

Figure 39. Reproduced image on CRT under illuminant “A”.
The minimum averaged perceptual Mahalanobis distance was 1.357 for \( \phi=0.95, \varepsilon=3, \beta=1.0, \gamma=1 \) and \( \alpha=0 \), coefficients of Eq. (7-8). The Eq. (7-8) can be rewritten as follows;

\[
\begin{align*}
    h' &= h, \quad (7-9 \text{ a}) \\
    C' &= C + 1, \quad (7-9 \text{ b}) \\
    L' &= 0.95L + 3, \quad (7-9 \text{ c})
\end{align*}
\]

The image was reproduced inside the color gamut of the CRT for 99.17% in red channel, 99.99% in the green channel, and 100.00% in the blue channel. The reproduced endoscopic image for these coefficients is shown in Fig. 40.

**Figure 40.** Reproduced stomach endoscopic image under illuminant “A”, for \( \phi=0.95, \varepsilon=3, \beta=1.0, \gamma=1 \) and \( \alpha=0 \) of Eq. (7-8).
This result shows that it is better to adjust metric lightness and chroma simultaneously and maintain the hue angle unchanged to minimize changes in the color appearance. The hue angle is the appearance attribute that can be distinguished with the highest precision and the psychophysical experiments showed that human visual system is very sensitive for changes in hue.

7.5 Conclusion
A method to reproduce endoscopic images on illuminated CRT was proposed. This color reproduction method uses color appearance models and gamut-mapping. Gamut-mapping was performed in 1976 CIELUV L*C*h color space by scaling and translation of the color attributes. A perceptual Mahalanobis distance was defined to evaluate the proposed gamut-mapping techniques. This perceptual distance is calculated using covariance matrix of perceptually equivalent metric lightness, chroma and hue angle and indicates how the color appearance of reproduced endoscopic image is affected by gamut-mapping. Experiments using this perceptual color distance showed that a mapping that minimizes changes in color appearance was obtained for $\phi=0.95$, $\epsilon=3$, $\beta=1.0$, $\gamma=1$ and $\alpha=0$, coefficients of Eq. (7-8). Therefore, it is better to map lightness and chroma simultaneously and maintain hue angle unchanged.
CHAPTER 8

CONCLUSION

Many aspects and problems involving color reproduction of original scene under various illuminants have been studied, specially for skin color and endoscopic images. At first, spectral reflectance of facial pattern images taken by HDTV camera was estimated using three principal components of skin spectral reflectance. Computer simulation of colorimetric color reproduction was done using those obtained spectral reflectance. The predicted images were reproduced colorimetrically on CRT and hardcopy. Color appearance models were also introduced into colorimetric color reproduction method to predict the color appearance of skin colors under various illuminants on CRT. Computer simulations of Fairchild, von Kries and LAB chromatic adaptation models were compared with the color hardcopies by psychophysical experiments using memory matching technique. These experiments showed that the incomplete chromatic adaptation model proposed by Fairchild can be used for a suitable prediction for color appearance of skin color patches. However, Fairchild model was not so effective for facial pattern images as skin color patches. Coefficients of Fairchild model were adjusted to reproduce facial pattern images by psychophysical experiments. The modified Fairchild model showed the best overall performance compared to the other color appearance models under various illuminants.
The proposed color reproduction method based on color appearance models was also applied to endoscopic image on CRT under environmental illumination. However, gamut-mapping is required for images that is not reproduced inside the gamut of CRT. From this experiment, we introduced a new perceptual color distance based on Mahalanobis distance for gamut-mapping. Mahalanobis distance was calculated using covariance matrix of metric lightness, chroma and hue angle obtained by psychophysical experiments. Therefore, I consider that the distance could be used as part of an extension of CIE 1994 total color-difference $\Delta E^{*}_{94}$ as perceptual color distance. Various gamut-mapping techniques were evaluated using this perceptual color distance. As a result, it was shown that the lightness and chroma should be mapped simultaneously preserving the hue angle for effective color reproduction of endoscopic image.

In this dissertation, the scope of the study was limited to specific application such as facial pattern and endoscopic image reproduction. However, I believe that the methods developed in this research can be extended to the reproduction of other types of complex images, such as fine art image, and landscape pictures.
REFERENCES


