EFFECT OF AMBIENT LIGHT ON COLOR APPEARANCE OF SOFTCOPY IMAGES

~ MIXED CHROMATIC ADAPTATION FOR SELF-LUMINOUS DISPLAYS ~

Naoya Katoh †, Kiyotaka Nakabayashi †, Masahiko Ito †, Shin Ohno ††

† Research Center, Sony Corporation,

6-7-35 Kita-shinagawa, Shinagawa, Tokyo 141-0001, Japan

†† B&P Company, Sony Corporation,

4-16-1 Okata, Atsugi, Kanagawa 243-0024, Japan

Keywords: Chromatic adaptation, Color reproduction, Color appearance, Softcopy images

ABSTRACT

With the widespread use of CMSs (color management systems), users are now able to achieve device independent color across different media. However, most of the current CMSs guarantee the same color only if one sees color under a controlled viewing condition. If one sees color under a different viewing condition, the reproduced color does not match the original. The effect of the ambient light on the color appearance of softcopy images is discussed in this paper. In a typical office environment, a computer graphic monitor with a CCT (correlated color temperature) of 9300K is widely used under F6 fluorescent light of 4150K CCT. In such a case, the human visual system is partially adapted to the CRT monitor's white point and partially to the ambient light. A new adaptation model: S-LMS is proposed to compensate for the mixed chromatic adaptation. Visual experiments were performed to evaluate the mixed chromatic adaptation [1, 2, 3]. Experimental results indicated that human visual system is 60% adapted to the monitor's white point and 40% to the ambient light when viewing softcopy images.

1 INTRODUCTION

With the widespread use of OS-based CMSs (color management systems) such as ColorSync 2.5 on MacOS or ICM 2.0 on Microsoft Windows, users are now able to achieve device independent color across different devices and media. These CMSs utilize ICC profiles [4] which store necessary information for the color characteristics of the devices. However, current CMSs hold some inevitable technical problems [37]. These problems include:

1. Device instability
2. Gamut differences between the devices
3. Color appearance differences
4. Lack of standard device characterization method
5. Lack of standard measurement method (including fluorescent measurement)
6. Lack of standard reference viewing condition

All of the above problems should be solved to achieve WYSIWYG (What You See Is What You Get) color reproduction [5, 6]. In this paper, appearance differences are discussed. Most of the current CMSs on PC market guarantee the same color only if one sees color under a certain controlled viewing condition [37]. If one sees color under a different viewing condition, the reproduced color does not match the original. On the other hand, the network environment enables users to send color images from one place to another that has a different viewing condition. In such a case, it is impossible to achieve the same color appearance with these CMSs.

Table 1 Comparison of Color Reproduction

	Application	Input	Output	Time	Place	Matching Method
1	* Color DTP	Monitor	Print	○	○	SMB
2	Color Copy	Print	Print	○	○	SMB
3	* Internet	Monitor	Monitor /Print	○/×	×	SMH
4	Color Fax	Print	Print	○/×	×	SMH
5	Video/Still Camera	Real Life	Monitor	×	×	MEM
6	Photography /Printing	Real Life	Print	×	×	MEM

○:same, ×: different

SMB: Simultaneous Binocular Matching Method

SMH: Simultaneous Haploscopic Matching Method

MEM: Memory Matching Method

Table 1 shows a comparison of various color reproduction applications. In the photography and the printing applications, one usually sees the reproduction sometime after one saw the original. In this case, the human visual system processes the image in one's memory and this process causes more saturated colors than the original color as a preferred color reproduction [7]. In the DTP (desktop publishing) applications, softcopy image and hardcopy images are viewed and compared simultaneously. Here, color appearance matching between the softcopy and the hardcopy image is necessary. Furthermore, in the internet publishing applications, images are often made on the CRT monitor screen as softcopy and then distributed to other places that has different viewing conditions. In these cases, compensation for the appearance differences caused by the different viewing becomes very important. The last column in the table 1: "matching method [8] " indicates the appropriate matching method for the visual experiments. When original image and its reproduction are compared simultaneously, either simultaneous binocular (SMB) method or simultaneous haploscopic (SMH) method would be an appropriate technique. Furthermore, when images are compared under same viewing condition, i.e., at the same place, simultaneous binocular (SMB) method is to be used [38, 39] and when images are compared under different viewing conditions, i.e., at the different places, simultaneous haploscopic (SMH) method is used to simulate different viewing condition for each eye [40, 41, 42]. In this study, the simultaneous binocular (SMB) method was applied for softcopy-vs-hardcopy matching experiments to simulate the DTP environment, and the simultaneous haploscopic (SMH) method was applied for softcopy-vs-softcopy matching experiments to simulate the network environment.

Matching between softcopy and hardcopy image involves another complicated issue, since softcopy images are self-luminous colors while hardcopy images are illuminated colors. The human visual system has two types of mechanisms for chromatic adaptation; sensory and cognitive [9]. Sensory mechanisms are those that act automatically in response to the given stimulus, such as retinal gain control. Cognitive mechanisms are those that rely on the observers' knowledge of the scene content. When hardcopy images are viewed, it could easily be perceived as an illuminated object, and both sensory and cognitive mechanisms are active. On the other hand, when softcopy images are viewed, cognitive mechanisms are not active and only sensory mechanisms are active, since it could not easily be interpreted as an illuminated object. CRT (cathode ray tube) monitors are often used as a soft proofing device for the hardcopy image output. However, what the user sees on the monitor does not match its output, even if the monitor and the output device are characterized with colorimetric values such as CIEXYZ or CIELAB. This is especially obvious when the CCT (correlated color temperature) of the CRT monitor's white point significantly differs from that of the ambient light. In a typical office environment, a computer graphic monitor having a CCT of 9300K is widely used in a room illuminated by F6 fluorescent light of 4150K CCT. Under such a viewing condition, it was hypothesized that the human visual system is partially adapted to the CRT monitor's white point and partially to the ambient light.

Several color appearance models [10 - 16, 43, 44] have already been proposed and some of the models produce very accurate predictions of color appearance [17, 18]. However, since they tried to predict color appearance for the complete range of viewing conditions, these models need a significant number of viewing condition parameters and are rather complex to implement. Furthermore, softcopy images viewed under mixed chromatic adaptation have not yet been evaluated. According to the CIE guideline for coordinated research to test color-appearance models for cross media color reproduction, it is assumed that observers have a fixed state of single adaptation [19, 20]. However, in a practical situation, when one is viewing an image on a CRT screen under a certain viewing condition, one's state of adaptation is affected by both the monitor's white point and the room illumination that are different. Also, one's eyes are not fixated at the CRT screen all the time, but sees the surrounding at intervals. Thus, one's state of chromatic adaptation is not a fixed at a single state. In this paper, the unfixed state of mixed chromatic adaptation on softcopy images is discussed. A new adaptation model: S-LMS is proposed to compensate for the mixed chromatic adaptation. This model is fundamentally based on von Kries adaptation model [21] and, in addition, "contrast difference" and "mixed adaptation" for the softcopy images are taken into account. Since the objective of this study was to provide a practical method for appearance matching for softcopy images, only the typical office environments were considered. Also, from an industrial point of view, compatibility with CIELAB should be very important, since CIELAB is currently accepted widely as a standard interchange color space. Thus, proposed adaptation model: S-LMS can be transformed to S-LAB, which is compatible with CIELAB.

The effect of ambient light on color appearance of CRT has been studied by several people. Brainard, et al. [22] and Choh, et al. [23] used an achromatic color matching method under a fixed state of chromatic adaptation. In the experiments of Brainard, et al., it was found that the adaptation shift from the monitor's white point caused by the ambient light was about 10-20% in CIE 1931/xy coordinates for a small test patch (1.35 x 1.35 deg.). Choh, et al. used a test patch of 2 x 2 deg. and defined the adaptation shift ratio in CIE 1976/u'v' coordinates. They performed the experiments for three different types of illuminants and at three levels of ambient luminance. When the CRT was set to 9300K and the ambient illuminance was F2, the shift from the monitor's white point was about 15%. In both Brainard's and Choh's experiments, the shift caused by the ambient illumination was subtle. This could be mainly explained by the fact that the observers' eyes were fixated at the CRT screen, thus the state of chromatic adaptation was more complete. Katoh [1, 2] and Berns, et al. [24] used pictorial images for cross-media color reproduction at mixed chromatic adaptation. In Katoh's experiment, softcopy images on the CRT screen were compared with the hardcopy image under an F6 illuminant. It was found that the human visual system was 60% adapted to the monitor's white point and 40% to the ambient light, when seeing softcopy images on a CRT screen (note that the adaptation shift from the monitor's white point was 40%). Berns, et al. have also performed visual experiments for a softcopy image viewed at a mixed state of chromatic adaptation compared with the hardcopy image. In their experiments, the luminance of monitor's peak white was set to 56.8 cd/m^2 and the luminance of paper white was 75.7 cd/m^2. Their results were similar to Katoh's previous experiment; an image with an adaptation shift of 50% was most preferred. For the cross-media comparisons, since ones' eyes are not fixated, it could be assumed that the human visual system is more affected by the ambient illumination than above achromatic experiments at a fixated state of chromatic adaptation.

2 DEVICE CHARACTERIZATION

Precise device characterization is essential for color matching experiments. Characterization methods for the CRT monitor and the continuous ink-jet printer used for the visual experiments are briefly described.

2.1 Monitor Characterization:

The CRT monitors used in the experiments were four computer graphic monitors: "Macintosh 16" Monitor", Sony "GDM-2036" and two Sony "GDM-2000TC's". These monitors were characterized by the method proposed by Berns [25] and CIE [26]. The model mainly consists of two stages; the tone-curve correction for the cathode-ray-tube characteristic and the additive color mixture of red, green and blue phosphors. The parameters necessary for the gamma-curve correction were derived from the eight ramp data of the primary colors (red, green, and blue), and the additive color mixture matrix was obtained by the regression technique[45] from thirty-two colors in IEC 61966-3[46]. Minolta color analyzer: CA-100 was used for the measurements. All the measurements were performed in dark room with black background to eliminate the flare[46], and flare term was added later according to surround luminance, as described in section 3. The performance of the monitor characterization is shown in table 2. It was evaluated by the twenty-four color patches that simulates the tristimulus values of Macbeth ColorChecker®.

$$
\begin{aligned}
R &= \frac{Y_R}{Y_{R,\max}} = \left\{ k_{r,gain}\left(\frac{dr}{255}\right) + k_{r,offset} \right\}^{\gamma_r} \\
G &= \frac{Y_G}{Y_{G,\max}} = \left\{ k_{g,gain}\left(\frac{dg}{255}\right) + k_{g,offset} \right\}^{\gamma_g} \\
B &= \frac{Y_B}{Y_{B,\max}} = \left\{ k_{b,gain}\left(\frac{db}{255}\right) + k_{b,offset} \right\}^{\gamma_b}
\end{aligned} \tag{1}
$$

$$
\begin{bmatrix} X_{(CRT)} \\ Y_{(CRT)} \\ Z_{(CRT)} \end{bmatrix} = \begin{bmatrix} X_{R,\max} & X_{G,\max} & X_{B,\max} \\ Y_{R,\max} & Y_{G,\max} & Y_{B,\max} \\ Z_{R,\max} & Z_{G,\max} & Z_{B,\max} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{2}
$$

Table 2 Performance of the Monitor Characterization

#	Monitor Model	Ave. Color Difference ± Std. Deviation
1	Apple 16" Monitor	ΔE*ab = 1.90 ± 1.28
2	Sony GDM-2036	ΔE*ab = 0.97 ± 0.41
3	Sony GDM-2000TC (A)	ΔE*ab = 0.83 ± 0.54
4	Sony GDM-2000TC (B)	ΔE*ab = 0.63 ± 0.70

2.2 Printer Characterization

The continuous ink jet printer Iris SmartJet 4012 was used as the hardcopy output device. A three-dimensional Lab-to-CMY look-up-table (LUT) was generated from measurement data of a 9x9x9 color chart evenly sampled in device color space by the method proposed by Hung[27]. For the colors that were outside the gamut of the printer, it was clipped to the surface of the printer's gamut. The gamut mapping technique will be discussed later in section 4. Gretag spectrophotometer: SPM-100 was used for the measurements. It has 45/0 measurement geometry, and F6 illuminant and 2 degree observer was used. The performance of the characterization was evaluated using the twenty-four color patches of the Macbeth ColorChecker® and shown in table 3.

Table 3 Performance of the Printer Characterization

Printer Model	Ave. Color Difference ± Std. Deviation
Iris SmartJet 4012	ΔE*ab =1.92 ± 0.96

3 ADAPTATION MODELING

Adaptation modeling used here essentially consists of three stages: 1) compensation for contrast variation, 2) transformation from tristimulus values to cone signals, and 3) compensation for chromatic adaptation.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \xrightarrow{\text{Contrast Compensation}} \begin{bmatrix} \overline{X}' \\ \overline{Y}' \\ \overline{Z}' \end{bmatrix} \xrightarrow{\tilde{M}} \begin{bmatrix} \overline{L} \\ \overline{M} \\ \overline{S} \end{bmatrix} \xrightarrow{\text{Chromatic Adaptation}} \begin{bmatrix} L/L_n \\ M/M_n \\ S/S_n \end{bmatrix} = \begin{bmatrix} L_S \\ M_S \\ S_S \end{bmatrix}$$

3.1 Contrast Compensation:

First, the contrast variation for softcopy images caused by the ambient light must be compensated. An important effect of ambient light is the variation of the perceived image contrast in accordance with the surround's luminance level. This contrast difference is mainly caused by the reflection of the ambient light on the CRT screen. The black on the CRT screen will not be dark enough because the reflection of the ambient light still exists, although most of the monitors have anti-glare filter on the surface of the CRT screen. Monitors have no means of producing black darker than this reflection. Since the human visual system is more sensitive to dark areas and less sensitive to light areas as the CIELAB equations imply, the contrast of the softcopy image will be weaker if the black is not dark enough. Therefore, in this experiment, this reflection was taken into consideration. This reflection of the ambient light on the CRT screen was added to the colors produced by the phosphors [28, 46]. "R_{bk}" is the reflectance factor of the CRT screen surface, usually 0.03 to 0.05. The subscript "$_{(CRT)}$"refers to the CRT monitor and "$_{(Ambient)}$"refers to the ambient light. After adding this reflection, the maximum value of "$Y'_{(CRT)}$"is normalized to one. The subscript "n" indicates the maximum value and "¯" indicates normalized value.

$$
\begin{aligned}
X'_{(CRT)} &= X_{(CRT)} + R_{bk} \; X_{(Ambient)} \\
Y'_{(CRT)} &= Y_{(CRT)} + R_{bk} \; Y_{(Ambient)} \\
Z'_{(CRT)} &= Z_{(CRT)} + R_{bk} \; Z_{(Ambient)}
\end{aligned}
\qquad (3)
$$

$$
\begin{aligned}
\overline{X'}_{(CRT)} &= \frac{X'_{(CRT)}}{Y'_{n(CRT)}} = \frac{X_{(CRT)} + R_{bk} \; X_{(Ambient)}}{Y_{n(CRT)} + R_{bk} \; Y_{(Ambient)}} \\
\overline{Y'}_{(CRT)} &= \frac{Y'_{(CRT)}}{Y'_{n(CRT)}} = \frac{Y_{(CRT)} + R_{bk} \; X_{(Ambient)}}{Y_{n(CRT)} + R_{bk} \; Y_{(Ambient)}} \\
\overline{Z'}_{(CRT)} &= \frac{Z'_{(CRT)}}{Y'_{n(CRT)}} = \frac{Z_{(CRT)} + R_{bk} \; X_{(Ambient)}}{Y_{n(CRT)} + R_{bk} \; Y_{(Ambient)}}
\end{aligned}
\qquad (4)
$$

Or, in matrix form:

$$
\begin{bmatrix} \overline{X'}_{(CRT)} \\ \overline{Y'}_{(CRT)} \\ \overline{Z'}_{(CRT)} \end{bmatrix} = \frac{1}{Y'_{n(CRT)}} \begin{bmatrix} X'_{(CRT)} \\ Y'_{(CRT)} \\ Z'_{(CRT)} \end{bmatrix} = \frac{1}{Y_{n(CRT)} + R_{bk} \; Y_{(Ambient)}} \left\{ \begin{bmatrix} X_{(CRT)} \\ Y_{(CRT)} \\ Z_{(CRT)} \end{bmatrix} + R_{bk} \begin{bmatrix} X_{(Ambient)} \\ Y_{(Ambient)} \\ Z_{(Ambient)} \end{bmatrix} \right\} \qquad (5)
$$

3.2 Transformation From Tristimulus Values To Cone Signals

Then, the tristimulus values are transformed into the human visual system's cone signals. The Hunt-Pointer-Estevez transformation matrix normalized to an equi-energy illuminant (E) is used here, since it is desirable to normalize the cone signals for equality for the self-luminous colors [10]. This matrix is also used in Hunt's color appearance model [10].

$$\begin{bmatrix} \overline{L}_{(CRT)} \\ \overline{M}_{(CRT)} \\ \overline{S}_{(CRT)} \end{bmatrix} = \begin{bmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0000 \end{bmatrix}_E \begin{bmatrix} \overline{X'}_{(CRT)} \\ \overline{Y'}_{(CRT)} \\ \overline{Z'}_{(CRT)} \end{bmatrix} \quad (6)$$

For the chromatic adaptation compensation which will be described next, the tristimulus values of monitor's white point must be transformed into cone signal beforehand.

$$\begin{bmatrix} \overline{L}_{n(CRT)} \\ \overline{M}_{n(CRT)} \\ \overline{S}_{n(CRT)} \end{bmatrix} = \begin{bmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0000 \end{bmatrix}_E \begin{bmatrix} \overline{X'}_{n(CRT)} \\ \overline{Y'}_{n(CRT)} \\ \overline{Z'}_{n(CRT)} \end{bmatrix} \quad (6')$$

3.3 Chromatic Adaptation Compensation

Finally, compensation is made for the change in adaptation according to the surroundings. The human visual system changes the cone sensitivity of each channel to get an image white-balanced as in color video cameras [21]. Basically, the simple von Kries adaptation model [21] is used, in which the signals of each channel are divided by the reference white's signals. However, the reference white point to which the human visual system adapts was investigated further in this study. There are two steps for the calculation of the adaptation white point; incomplete adaptation and mixed adaptation.

3.3.1 Incomplete Adaptation

The first step in the adaptation point calculation is the compensation for the incomplete chromatic adaptation of the human visual system for the self-luminous displays. Even if the monitor is placed in a totally dark room, the human visual system's adaptation to a CRT monitor's white point will not be complete. Adaptation becomes less complete as the chromaticity of the adapting stimulus deviates from the illuminant E and as the luminance of the adapting stimulus decreases [29 - 33]. The incomplete adaptation point can be expressed as below. "p_L, p_M, p_S" are the chromatic adaptation factors for the illuminant E used in Hunt's color appearance model [10].

$$\begin{aligned} \overline{L'}_{n(CRT)} &= \overline{L}_{n(CRT)} / p_L \\ \overline{M'}_{n(CRT)} &= \overline{M}_{n(CRT)} / p_M \\ \overline{S'}_{n(CRT)} &= \overline{S}_{n(CRT)} / p_S \end{aligned} \tag{7}$$

$$\begin{aligned} p_L &= \left(1 + Y'^{1/3}_{n(CRT)} + l_E\right) / \left(1 + Y'^{1/3}_{n(CRT)} + 1/l_E\right) \\ p_M &= \left(1 + Y'^{1/3}_{n(CRT)} + m_E\right) / \left(1 + Y'^{1/3}_{n(CRT)} + 1/m_E\right) \\ p_S &= \left(1 + Y'^{1/3}_{n(CRT)} + s_E\right) / \left(1 + Y'^{1/3}_{n(CRT)} + 1/s_E\right) \end{aligned} \tag{8}$$

$$\begin{aligned} l_E &= 3\ \overline{L}_{n(CRT)} / (\overline{L}_{n(CRT)} + \overline{M}_{n(CRT)} + \overline{S}_{n(CRT)}) \\ m_E &= 3\ \overline{M}_{n(CRT)} / (\overline{L}_{n(CRT)} + \overline{M}_{n(CRT)} + \overline{S}_{n(CRT)}) \\ s_E &= 3\ \overline{S}_{n(CRT)} / (\overline{L}_{n(CRT)} + \overline{M}_{n(CRT)} + \overline{S}_{n(CRT)}) \end{aligned} \tag{9}$$

Or, in matrix form:

$$\begin{bmatrix} \overline{L'}_{n(CRT)} \\ \overline{M'}_{n(CRT)} \\ \overline{S'}_{n(CRT)} \end{bmatrix} = \begin{bmatrix} 1/p_L & 0 & 0 \\ 0 & 1/p_M & 0 \\ 0 & 0 & 1/p_S \end{bmatrix} \begin{bmatrix} \overline{L}_{n(CRT)} \\ \overline{M}_{n(CRT)} \\ \overline{S}_{n(CRT)} \end{bmatrix} \tag{10}$$

3.3.2 Mixed Adaptation

The next step is the compensation for mixed chromatic adaptation. In a typical office setting, softcopy images are rarely seen under dark conditions. The room is normally illuminated with fluorescent lighting having a CCT around 4150K. The CCT of the widely-used computer graphic monitor's default white point is much higher than this lighting, usually around 9300K. In cases where both white points are different, it was hypothesized that the human visual system is partially adapted to the monitor's white point and partially to the ambient light's white point. Therefore, the adapting stimulus for the human visual system for softcopy images can be expressed as the inter-mediate point of the two as shown in the equations below. "R_{adp}" is the adaptation ratio to the monitor's white point, "$Y'_{n(CRT)}$" is the absolute luminance of the monitor's white point, and "$Y_{n(Ambient)}$" is the absolute luminance of the ambient light. When the ratio equals 1.0, the human visual system is assumed to be completely adapted to the monitor's white point and none to the ambient light. This case is conceptually close to CIELAB matching, which incorporates complete white point adaptation in CIEXYZ coordinates. Conversely, when the ratio is 0.0, the human visual system is assumed to be totally adapted to the ambient light and none to the monitor's white. This case is conceptually close to CIEXYZ matching, which is merely colorimetric match without white point adaptation. These two cases assumes that the human visual system is at single -state chromatic adaptation.

$$
\begin{aligned}
\overline{L''}_{n(CRT)} &= R_{adp}\left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3}\overline{L'}_{n(CRT)} + (1-R_{adp})\left(\frac{Y_{n(Ambient)}}{Y_{adp}}\right)^{1/3}\overline{L}_{n(Ambient)} \\
\overline{M''}_{n(CRT)} &= R_{adp}\left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3}\overline{M'}_{n(CRT)} + (1-R_{adp})\left(\frac{Y_{n(Ambient)}}{Y_{adp}}\right)^{1/3}\overline{M}_{n(Ambiebt)} \\
\overline{S''}_{n(CRT)} &= R_{adp}\left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3}\overline{S'}_{n(CRT)} + (1-R_{adp})\left(\frac{Y_{n(Ambient)}}{Y_{adp}}\right)^{1/3}\overline{S}_{n(Ambient)}
\end{aligned}
\qquad (11)
$$

$$
\text{where}\quad Y_{adp} = \left\{R_{adp}\, {Y'_{n(CRT)}}^{1/3} + (1-R_{adp})\, {Y_{n(Ambient)}}^{1/3}\right\}^{3}
$$

The weighting factors: "$(Y'_{n(CRT)}/Y_{adp})^{1/3}$, $(Y_{n(Ambient)}/Y_{adp})^{1/3}$" in equation (11) were introduced to correspond to the luminance difference. When the luminance of the CRT: "$Y'_{n(CRT)}$" equals the ambient luminance: "$Y'_{n(Ambient)}$", equation (11) is reduced to the equation (12).

$$
\begin{aligned}
\overline{L''}_{n(CRT)} &= R_{adp}\ \overline{L'}_{n(CRT)} + (1 - R_{adp})\ \overline{L}_{n(Ambient)} \\
\overline{M''}_{n(CRT)} &= R_{adp}\ \overline{M'}_{n(CRT)} + (1 - R_{adp})\ \overline{M}_{n(Ambiebt)} \\
\overline{S''}_{n(CRT)} &= R_{adp}\ \overline{S'}_{n(CRT)} + (1 - R_{adp})\ \overline{S}_{n(Ambient)}
\end{aligned}
\qquad (12)
$$

With the newly-defined white points for the softcopy images, the von Kries adaptation model is applied. Thus, the viewing-condition independent index: S-LMS can be expressed as below. The subscript "$_S$" stands for the "Softcopy".

$$
\begin{aligned}
L_S &= \overline{L}_{(CRT)} / \overline{L''}_{n(CRT)} \\
M_S &= \overline{M}_{(CRT)} / \overline{M''}_{n(CRT)} \\
S_S &= \overline{S}_{(CRT)} / \overline{S''}_{n(CRT)}
\end{aligned}
\qquad (13)
$$

Or, in matrix form:

$$
\begin{bmatrix} L_S \\ M_S \\ S_S \end{bmatrix} =
\begin{bmatrix} 1/\overline{L''}_{n(CRT)} & 0 & 0 \\ 0 & 1/\overline{M''}_{n(CRT)} & 0 \\ 0 & 0 & 1/\overline{S''}_{n(CRT)} \end{bmatrix}
\begin{bmatrix} \overline{L}_{(CRT)} \\ \overline{M}_{(CRT)} \\ \overline{S}_{(CRT)} \end{bmatrix}
\qquad (14)
$$

For the hardcopy, the simple von Kries chromatic adaptation without contrast compensation, incomplete adaptation and mixed adaptation is used. Here, the media white (or "paper white") is chosen as the reference white, because the eye tends to adapt according to the perceived whitest point of the scene[47]. It should be noted, however, that reference white must be carefully chosen when paper white is not white enough.

$$\begin{bmatrix} \bar{L}_{(Print)} \\ \bar{M}_{(Print)} \\ \bar{S}_{(Print)} \end{bmatrix} = \begin{bmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0000 \end{bmatrix}_E \begin{bmatrix} \bar{X}_{(Print)} \\ \bar{Y}_{(Print)} \\ \bar{Z}_{(Print)} \end{bmatrix} \qquad (15)$$

$$\begin{bmatrix} \bar{L}_{n(Print)} \\ \bar{M}_{n(Print)} \\ \bar{S}_{n(Print)} \end{bmatrix} = \begin{bmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0000 \end{bmatrix}_E \begin{bmatrix} \bar{X}_{n(Print)} \\ \bar{Y}_{n(Print)} \\ \bar{Z}_{n(Print)} \end{bmatrix} \qquad (15')$$

$$\begin{aligned} L_S &= \bar{L}_{(Print)} / \bar{L}_{n(Print)} \\ M_S &= \bar{M}_{(Print)} / \bar{M}_{n(Print)} \\ S_S &= \bar{S}_{(Print)} / \bar{S}_{n(Print)} \end{aligned} \qquad (16)$$

Or, in matrix form:

$$\begin{bmatrix} L_S \\ M_S \\ S_S \end{bmatrix} = \begin{bmatrix} 1/\bar{L}_{n(Print)} & 0 & 0 \\ 0 & 1/\bar{M}_{n(Print)} & 0 \\ 0 & 0 & 1/\bar{S}_{n(Print)} \end{bmatrix} \begin{bmatrix} \bar{L}_{(Print)} \\ \bar{M}_{(Print)} \\ \bar{S}_{(Print)} \end{bmatrix} \qquad (17)$$

If necessary, S-LMS could be transformed into S-XYZ using the inverse of the Hunt-Pointer-Estevez transformation matrix normalized to illuminant E, and then to S-LAB or S-LCh.

$$\begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} = \begin{bmatrix} 1.9102 & -1.1122 & 0.2019 \\ 0.3709 & 0.6291 & 0.0000 \\ 0.0 & 0.0 & 1.0000 \end{bmatrix}_E \begin{bmatrix} L_S \\ M_S \\ S_S \end{bmatrix} \qquad (18)$$

$$L_S^* = 116\ \left(Y^S\right)^{1/3} - 16$$
$$a_S^* = 500\ \left\{\left(X_S\right)^{1/3} - \left(Y_S\right)^{1/3}\right\} \qquad (19)$$
$$b_S^* = 200\ \left\{\left(Y_S\right)^{1/3} - \left(Z_S\right)^{1/3}\right\}$$

$$C_S^* = \sqrt{\left(a_S^*\right)^2 + \left(b_S^*\right)^2}$$
$$h_S^\circ = \tan^{-1}\left(\frac{a_S^*}{b_S^*}\right) \qquad (20)$$

4 IMAGE TRANSFORMATION

The flow of the image transformation is indicated in figure 1. In this adaptation model, necessary viewing condition parameters are; 1) absolute luminance of the monitor's white point, 2) the chromaticity of the ambient light, and 3) the absolute luminance of the ambient light.

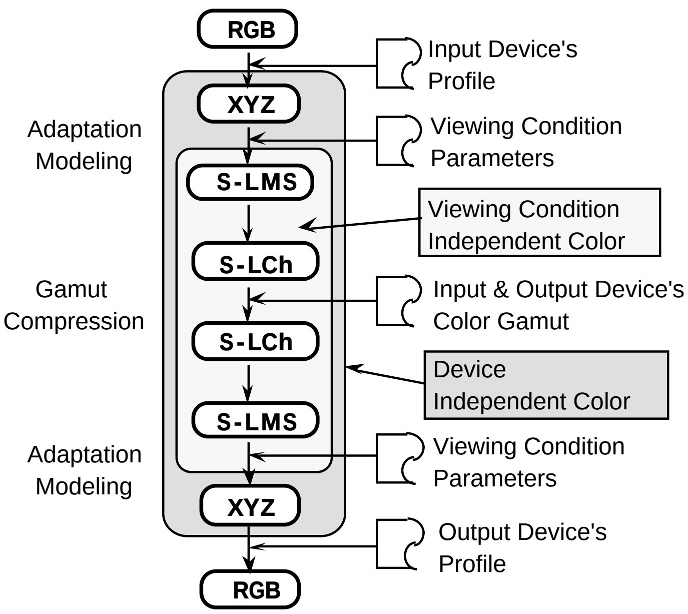


Fig. 1 Flow of the Image Transformation

1. RGB data are transformed to XYZ using the input device's device characteristics.
2. XYZ data are then transformed into S-LMS using the above adaptation model with the input device's viewing condition parameters at a certain adaptation ratio. For softcopy image transformation, equations (5), (6), (10), (14) are used and for hardcopy image transformation, equations (15), (17) are used.
3. If necessary, S-LMS are transformed into S-LAB or S-LCh using equations (18), (19), (20) for gamut compression. Colors outside the output device's gamut were mapped towards the achromatic axis while keeping hue: "h_s" and lightness: "L_s" constant. Then, the mapped S-LAB or S-LCh are transformed back to S-LMS.
4. S-LMS data are transformed back to XYZ using the inverse of step 2 with the output device's viewing condition parameters at the same adaptation ratio used above.
5. XYZ are transformed to RGB using the output device's device characteristics.

Many gamut mapping techniques are proposed for various applications [34]. However, the investigation of gamut mapping is out of the scope of this study. Instead, the images that do not contain much out-of-gamut colors were chosen and used for the experiments (see figure 9 and 10).

5 VISUAL EXPERIMENTS

The following visual experiments were performed to find the best adaptation ratio: "R_{adp}". Three images were used; image A and B were portrait images and image C was an image of macaws. The image A was the portrait of a lady wearing a yellow shirt, a red cap and holding blue and green objects, with grayish background and the image B was the portrait of a lady sitting at a table with many still objects. The image C is the image of two macaws with greenish background; one macaw is cyan and yellow and the other is red. The images are shown in figure 9 and the histograms of the image pixels in a*b* coordinates are indicated in figure. 10.

Table 4 Configuration of Visual Experiments

Exp.	Matching	Monitor's White Point	Ambient Light (Paper White)	Images	# of Obs.	Method
#1	SC vs. HC	#1: ~6500K (87.4 cd/m^2) #2: ~9000K (121.0 cd/m^2)	F6: 4150K (~100 cd/m^2)	A	15	SMB
#2	SC vs. HC	# 2: 9340K (99.8 cd/m^2)	F6: 4150K (183.4 cd/m^2) F6: 4150K (297.8 cd/m^2)	A, B, C	18	SMB
#3	SC vs. SC	#3: 6530K (80.2 cd/m^2): A vs. #4: 9370K (80.5 cd/m^2): B	4180K (124 cd/m^2) 3490K (150 cd/m^2)	A, B	24	SMH

SC: Softcopy image / HC: Hardcopy images

SMB: Simultaneous Binocular matching method

SMH: Simultaneous Haploscopic matching method

5.1 Experiment #1: Softcopy-vs-Hardcopy Matching at the Same Luminance Level

First, visual experiments were performed between softcopy image and hardcopy image at similar luminance levels. The room had a fluorescent (F6: 4150K) lighting. A white paper set next to the monitor had a luminance around 100 cd/m^2. In our experiments, paper white was chosen as the reference white point for the hardcopy reproduction, as described earlier. The same experiments were replicated for two monitors with different white points; 6500K (87.4 cd/m^2) and 9000K (121 cd/m^2). Image A was used in this experiment. Fifteen color-normal observers (12 male and 3 female: ages from 23 to 38) participated. The image (1536 x 1024 pixels: RGB 8 bits) was displayed on the CRT screen at 72 dpi at a half of its size (177 mm x 267 mm), so that image size will be similar to hardcopy reproduction. An image displayed on the CRT screen was surrounded by 100% white proximal field of 5 mm wide, with 100% white patches as a reference in the 20% uniform gray background. An. Hardcopy images transformed through the procedure above were reproduced by the Iris SmartJet printer at a resolution of 150 dpi (171 mm x 256 mm). Images at six levels of the softcopy adaptation ratio: "R_{adp} " (0, 20, 40, 60, 80, 100%) were reproduced and used for the paired comparison experiment. Since the luminance levels were similar, equation (12) was used instead of equation (11). Fifteen pairs were formed from these six images. Before the experiment, observers were given approximately five minutes to adapt to the viewing conditions of the room. The observer was instructed to sit approximately 50-60 cm from the screen and to identify the better matched image to the softcopy image on the monitor from a given pair of hardcopy images. The simultaneous binocular (SMB) matching method was applied. The observer could move the pair of images anywhere he desired, but not on the screen next to the softcopy image, so that the observer had to move his eyes at some distances for the image comparisons. No time restriction was placed on the observers. Using Thurstone's law of comparative judgment [48], ordinal-scale visual decisions were converted to the interval psychophysical scale. Examples of output images at different adaptation ratio are shown in figure 11.

5.2 Experiment #2: Softcopy-vs-Hardcopy Matching at Different Luminance Levels

Next, two other series of experiments were performed under two different luminance levels of the fluorescent (F6: 4150K) lighting. A white paper set next to the monitor had a luminance of 183.4 cd/m^2 and 297.8 cd/m^2 , respectively. The absolute luminance of the CRT monitor's white point was set to 99.8 cd/m^2 , and its CCT was 9340K. Other configurations were the same as in experiment #1. Three images (A, B, C) were used for the visual experiments. Eighteen color-normal observers (16 male and 2 female: ages from 25 to 41) participated. Examples of output images at different luminance levels are shown in figure 12.

5.3 Experiment #3: Softcopy-vs-Softcopy Matching

Finally, visual experiments were performed for the softcopy image matching between two monitors with different white points. The experimental setup is indicated in figure 2. A simultaneous haploscopic (SMH) method was applied in this experiment to simulate different viewing conditions for each eye. A chin rest was used to fixate observer's face and a dividing wall was placed between two monitors, so that each eye will adapt to a different viewing condition. There was no ceiling over the top of the box, so that ambient illumination could light both of the observer's eyes. All the walls of the viewing box was set to gray at Munsell value of N8. It should be noted that observers could not view the images on the two monitors at the same time and had to move their eyes for the image comparison, since the monitors were placed at a certain distance.

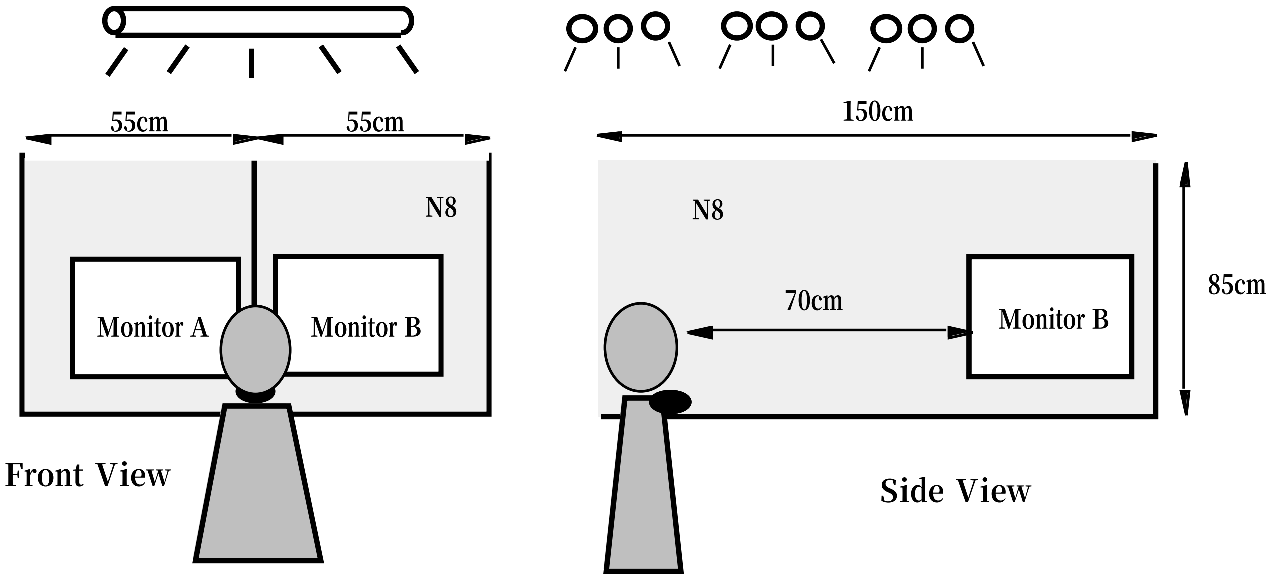


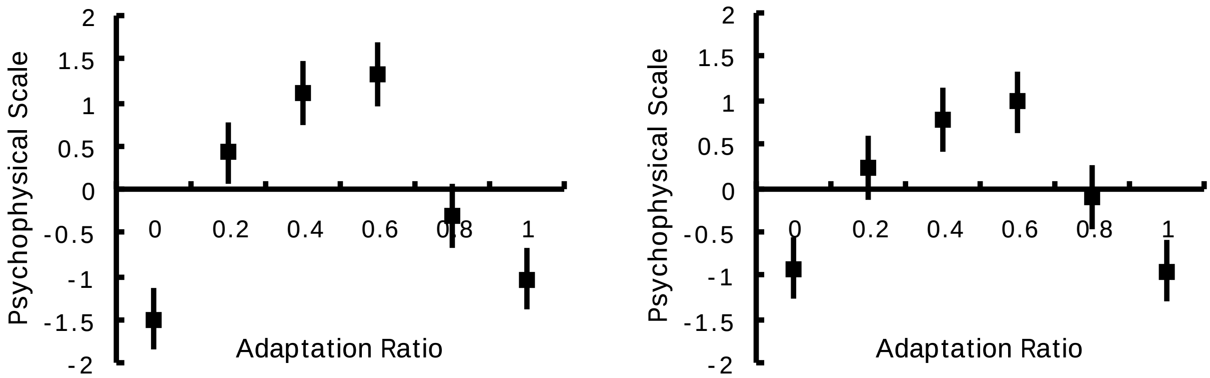
Fig. 2 Setup for Visual Experiment #3

Monitor A's white point was set to 6530K and its luminance to 80.2 cd/m^2, and monitor B's white point was set to 9370K and its luminance to 80.5 cd/m^2. The same experiment was replicated under two different fluorescent lamps; 4183K (124 cd/m^2) and 3486K (150 cd/m^2). Two portrait images (A, B) were used for the visual experiments. Twenty-four color-normal observers (23 male and 1 female: ages from 26 to 55) participated. The original image (512 x 341 pixels: RGB 8 bits) was displayed on the monitor A at a size of 163 mm x 108 mm with a 100% white proximal field 5 mm wide in a 20% uniform gray background. Images at six levels of the softcopy adaptation ratio: "R_{adp}" were reproduced on monitor B with the same proximal field and background as monitor A, and were used for the paired comparison experiment. Observers sat 70 cm from the screen and were instructed to identify the better matched reproduced image on monitor B to the original image on monitor A from a given pair. An X-window program was used for displaying and switching between the pair of images.

6 RESULTS

6.1 Experiment #1: Softcopy-vs-Hardcopy Matching at the Same Luminance Level

Figure 3 shows the results of visual experiment #1. The abscissa is the adaptation ratio defined in 3.3.2, and the ordinate is the psychophysical scale that indicates which image was most preferred. The error bars show the 95% confidence interval.



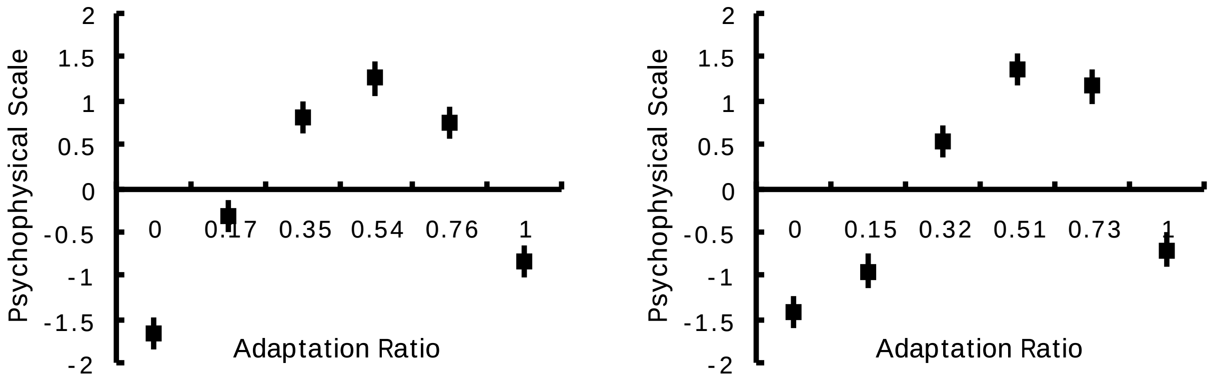
a) Monitor's White Point: ~6500K   b) Monitor's White Point: ~9000K

Fig. 3 Results of Experiment #1

The most preferred image was 60% adapted to the CRT monitor for both cases. The 40% CRT-adapted image was the next preferred one. The 100% CRT-adapted and the 100% ambient-light-adapted (i.e., 0% CRT-adapted) image had the two lowest scores, meaning that images at single-state chromatic adaptation were unacceptable reproduction for the softcopy color. Even though the two monitors used in this experiment had different white points, almost the same trend was found in both experimental results. This indicates that the adaptation ratio is independent of the CCT of the monitor's white point.

6.2 Experiment #2: Softcopy-vs-Hardcopy Matching at Different Luminance Levels

Figure 4 shows the result of visual experiment #2 for all the three images at two different luminance levels. It should be noted that the adaptation ratio was calculated differently, because the weighting factors in equation (11) was determined after this experiment. The weighting factors without the third power in equation (11) was used for image transformation and the ratio was later transformed to fit equation (11). Thus, the abscissa differs from experiment #1 (0, 20, 40, 60, 80, 100%). It was found that the images at adaptation ratio around 50% was most preferred and the single-state adapted images (0% and 100%) had low scores.



a) Luminance Level: 183.4 cd/m^2 b) Luminance Level: 297.8 cd/m^2

Fig. 4 Results of Experiment #2

Figure 5 shows the experimental results of experiments #1 and #2 at different luminance levels on the same plot. Although experiment #1 had a slightly different configuration from experiment #2, very similar trends were found for all the luminance levels. This indicates that adaptation ratio is independent of the luminance levels of ambient light. Figure 6 shows the results for visual experiment #2 for each image at two different luminance levels. As readily seen from the figure, the results did not depend on the image content. It should be noted, however, that Image C in figure 6 b) indicated different behavior than other images at 0% adaptation ratio. This is due to the fact that S-LMS involves white point shift, when the adaptation ratio was set to small. In such cases, some of the high-light colors will be out-of-gamut and these color will not be reproduced correctly. Since image C included many of yellow pixels which are high-light colors, and simple chroma-clipping was used for the gamut mapping, images at small adaptation ratio had a gamut mapping problem.

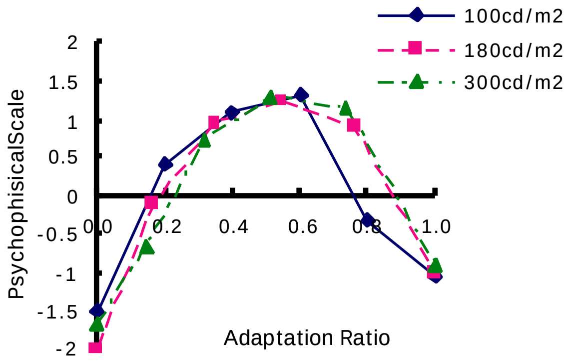
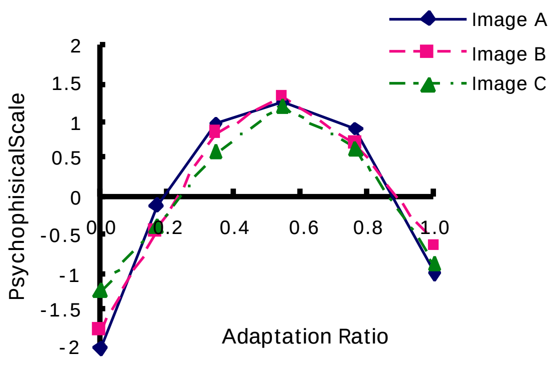
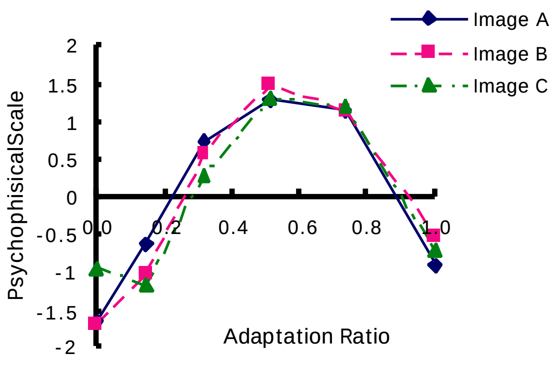


Image A

Fig. 5 Experimental Results at Different Luminance Levels



a) Luminance Level: 183.4 cd/m²

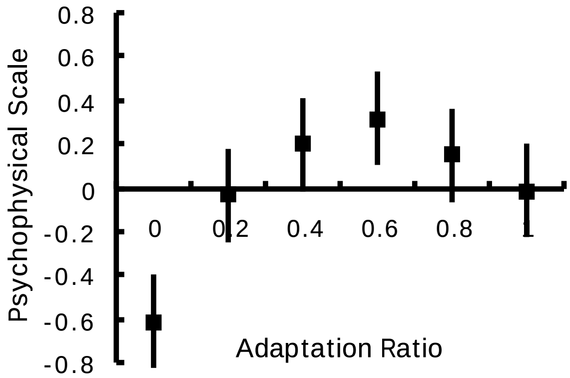


b) Luminance Level: 297.8 cd/m²

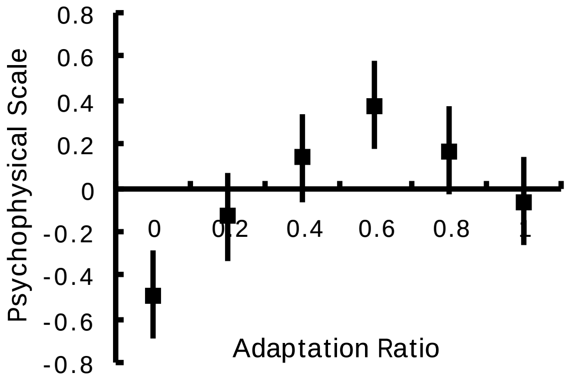
Fig. 6 Experimental Results with Different Images

6.3 Experiment #3: Softcopy-vs-Softcopy Matching

Figure 7 shows the results of experiment #3 at two different ambient illumination conditions. The most preferred images were at an adaptation ratio of 60%, while the image at the adaptation ratio of 0% adapted image had the worst scores for both cases. These results were similar to the previous experiments of softcopy-vs-hardcopy matching experiments, in which the adaptation ratio was also 60%.



a) Ambient Illumination: 4180K



b) Ambient Illumination: 3490K

Fig. 7 Results of Experiment #3

For all the experiments (#1 to #3), the reproduced softcopy image with adaptation ratio around 60% had the best scores. Most of the observers stated that these images using S-LMS had an acceptable match to the original image and had much better reproduction than single-state adapted images; i.e., CIEXYZ-matched or CIELAB-matched images.

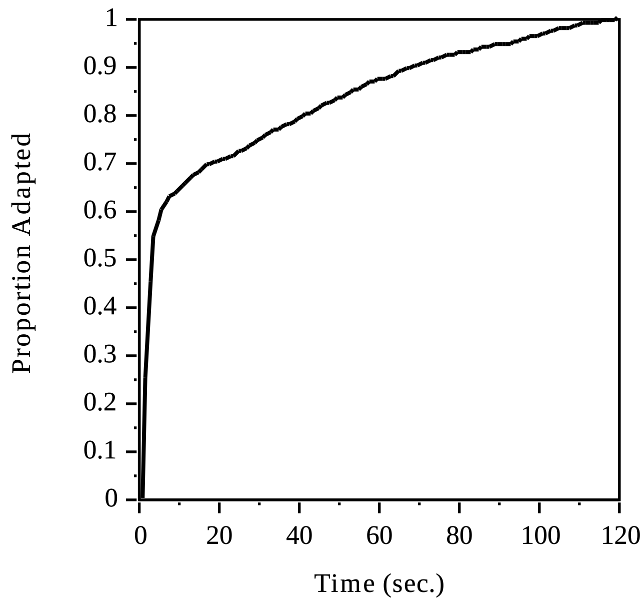
7 DISCUSSION

It has been believed that the adaptation mechanisms take as long as tens of minutes or even an hour. But this belief only applies to the lightness adaptation, not to the chromatic adaptation. Fairchild and

Lennie have measured the time course of chromatic adaptation [35] and found that the chromatic mechanisms were very rapid, in the order of tens of seconds. Fairchild and Reniff later extended their study [36] and indicated the possibility of two mechanisms for chromatic adaptation, the first being a rapid mechanism with a time constant of 0.9 to 1.5 second, and the second being a slower mechanism with a time constant of 38 to 53 second. The general form of such a function is expressed as;

$$Y = 1.0 - \left[K_1 \exp(-X_1 t) + K_2 \exp(-X_2 t)\right] \quad (21)$$

where "Y" is the proportion adapted, "t" is the adapting duration, "K_1" and "K_2" are scaling factors and "X_1" and "X_1"are the exponential time constants of the two mechanisms [36]. The overall average response for six conditions and three observers from their experimental results is shown in figure 8 [9]. According to their result, the human visual system's adaptation reaches 60% very quickly in a few seconds, but after that it takes almost two minutes to reach 100% adaptation.



M. D. Fairchild (1993) [9]

Fig. 8 Degree of Adaptation as a Function of Adapting Duration

In the present experiments, no time restriction for the image comparison was posed on observers. Most of the observers viewed the images back and forth at a few seconds intervals. If the basic state of observer's adaptation was 0% adapted to the monitor and 100 % to the ambient light, his state of chromatic adaptation would quickly be shifted to the monitor's white point as in figure 8 when an observer starts viewing a monitor. And when the observer's eyes go away from the softcopy image on the CRT monitor, his state of adaptation would quickly go back to the basic state. These results would explain why the 60%-adapted images had the best score in the present experiments. However, when the state of chromatic adaptation is fixed to single state, i.e., when observers were forced to see each image for a few minutes, his state of chromatic adaptation becomes almost complete to each viewing condition. This also explains why experimental results of both Brainard[22] and Choh[23] had a very little shift from the complete adaptation. Therefore, the experimental results would have been different, if successive binocular method (SCB)[18, 19, 20] with time restriction was applied for the visual experiments.

8 CONCLUSION

The experimental results indicated that the human visual system is 60% adapted to the monitor's white point and 40% to the ambient light comparing softcopy image with other images under ambient illumination. This applies both for softcopy-vs-hardcopy matching and softcopy-vs-softcopy matching experiments. The adaptation ratio was found to be independent of the image content, the ambient luminance level and the monitor's white point. Appearance-matched images using the S-LMS adaptation model reproduces much better matching images than the reproduction of CMSs that assumes a single state of adaptation. This method could be used from hardcopy input to softcopy display, and conversely from softcopy display to hardcopy output since this method is reversible. Therefore, this mixed chromatic adaptation model: S-LMS can improve the softcopy color reproduction.

9 ACKNOWLEDGMENT

I would like to express my sincere gratitude to Dr. Roy S. Berns and Dr. Mark D. Fairchild of Munsell Color Science Laboratory, Rochester Institute of Technology, for stimulating technical discussions and valuable advice. I would also like to thank all of the observers for their patience.

REFERENCES

1. N. Katoh, "Practical Method for Appearance Match between Soft Copy and Hard Copy," SPIE 2170, 170-181 (1994)
2. N. Katoh, "Appearance Match between Soft Copy and Hard Copy under Mixed Chromatic Adaptation," Proc. IS&T/SID Color Imaging Conf. 3, 22-25 (1995)
3. N. Katoh, K. Nakabayashi, "Effect of Ambient Light on Color Appearance of Soft Copy Images," Proc. AIC Color 97 Kyoto, 2, 582-585 (1997)
4. ICC Profile Format Specification ver. 3.4, International Color Consortium (Aug., 1997)
5. R. S. Berns, "Color WYSIWYG: A Combination of Device Colorimetric Characterization and Appearance Modeling," SID 92 Digest, 549-552 (1992)
6. M. D. Fairchild, "Some Hidden Requirements for Device-Independent Color Imaging," SID 94 Digest, 865-868 (1994)
7. R. W. G. Hunt, "The Reproduction of Colour in Photography, Printing & Television, Fifth Edition," Fountain Press, England (1995)
8. K. M. Braun, et al., "Viewing Techniques for Cross-Media Image Comparisons," Color Res. Appl. 21, 6-17 (1996)
9. M. D. Fairchild, "Chromatic Adaptation in Hard-copy/Soft-copy Comparisons," SPIE 1912, 14-61 (1993)
10. R. W. G. Hunt, "Revised Colour-Appearance Model for Related and Unrelated Colours," Color Res.

Appl. 16 , 146-165 (1991).

11. R. W. G. Hunt, "An Improved Predictor of Colourfulness in a Model of Colour Vision," Color Res. Appl. 19 , 178-190 (1993)
12. Y. Nayatani, et al., "Color Appearance Model and Chromatic-Adaptation Transform," Color Res. Appl. 15 , 210-221 (1990)
13. Y. Nayatani, et al., "Lightness Dependency of Chroma Scales of a Nonlinear Color-Appearance Model and Its Latest Formulation," Color Res. Appl. 120 , 156-167 (1995)
14. M. D. Fairchild, R. S. Berns, "Image Color-Appearance Specification Through Extension of CIELAB," Color Res. Appl. 18 , 178-190 (1993)
15. M. D. Fairchild, "Refinement of the RLAB Color Space," Color Res. Appl. 21 , 338-346 (1996)
16. M. R. Luo, et al., "The LLAB (l:c) Colour Model," Color Res. Appl. 21 , 412-429 (1996)
17. M. R. Luo, et al., "Quantifying Colour Appearance. Part II. Testing Colour Models Performance Using LUTCHI Colour Appearance Data," Color Res. Appl. 16 , 181-197 (1991)
18. K. M. Braun, M. D. Fairchild, "Testing Five Color-Appearance Models for Changes in Viewing Conditions," Color Res. Appl. 22 , 165-174 (1997)
19. M. D. Fairchild (CIE TC 1-34), "Testing Colour-Appearance Models: Guidelines for Coordinated Research," Color Res. Appl. 20 , 262-267 (1995)
20. P. J. Alessi (CIE TC 1-27), "CIE Guidelines for Coordinated Research on Evaluation of Colour Appearance Models for Reflection Print and Self-Luminous Display Image Comparisons," Color Res. Appl. 19 , 48-58 (1994)
21. J. von Kries, "Chromatic Adaptation, Festschrift der Albrecht-Ludwig-Unversität," (Fribourg) (1902) (English Translation: D. L. MacAdam, Sources of Color Science, MIT Press, Cambridge (1970))
22. D. H. Brainard, K. Ishigami, "Factors Influencing the Appearance of CRT Colors," Proc. IS&T/SID Color Imaging Conf. 3 , 62-66 (1995)
23. K. H. Choh, et al, "Effects of Ambient Illumination on the Appearance of CRT Colors," Proc. IS&T/SID Color Imaging Conf. 4 , 224-226 (1996)

24. R. S. Berns, K. H. Choh, "Cathode-Ray-Tube to Reflection-Print Matching under Mixed Chromatic Adaptation Using RLAB," J. Elec. Imaging 4, 347-359 (1995)

25. R. S. Berns, "Methods for Characterizing CRT Displays," Displays, 16, 173-182, (1996)

26. CIE Technical Report 122, "The Relationship between Digital and Colorimetric Data for Computer Controlled CRT Displays," (1996)

27. P. C. Hung, "Colorimetric Calibration in Electronic Imaging Devices Using Look-up-Table model and Interpolations," J. Elec. Imaging 2, 53-61 (1993)

28. N. Katoh, T. Deguchi, "Reconsideration of CRT Monitor Characteristics," Proc. IS&T/SID Color Imaging Conf. 5, 33-40 (1997)

29. M. D. Fairchild, "Formulation and Testing of an Incomplete-Chromatic-Adaptation Model," Color Res. Appl. 16, 243-250 (1991)

30. M. D. Fairchild, "Chromatic Adaptation to Image Displays," TAGA Proc. 2, 803-823 (1992)

31. Y. Nayatani, "Examination of Adaptation Coefficients for Incomplete Adaptation," Color Res. Appl. 22, 156-164 (1997)

32. Y. Nayatani, et al., "Field Trials of a Nonlinear Color-Appearance Model," Color Res. Appl. 22, 240-258 (1997)

33. Y. Nayatani, "A Simple Estimation Method for Effective Adaptation Coefficient," Color Res. Appl. 22, 259-268 (1997)

34. N. Katoh, M. Ito, "Gamut Compression for Computer Generated Images (II)," Proc. IS&T/SID Color Imaging Conf. 4, 126-129 (1996)

35. M. D. Fairchild, P. Lennie, "Chromatic Adaptation to Natural and Incandescent Illuminants," Vision Research 32, 2077-2085 (1992)

36. M. D. Fairchild, L. Reniff, "Time Course of Chromatic Adaptation for Color-Appearance Judgments," J. Opt. Soc. Am. A 12, 824-833 (1995)

37. L. MacDonald, "Colour management and Display Calibration," Proc. CIE Expert Symposium '96: Colour Standards for Image Technology, 63-69, (1996)

38. S. M. Newhall, et al., "Comparison of Successive with Simultaneous Color Matching," J. Opt. Soc.

Am. 47 , 43-56 (1957)

39. R. W. G. Hunt, L. M. Winter, “Colour Adaptation in Picture Viewing Situations,” J. Phot. Sci. 23 , 112-115 (1975)

40. W. D. Wright, “The Measurement and Analysis of Colour Adaptation Phenomena,” Proc. Roy. Soc. 115B, 49-87 (1934)

41. E. J. Breneman “Corresponding Chromaticities for Different States of Adaptation to Complex Fields,” J. Opt. Soc. Am. A 4 , 1115-1129 (1987)

42. Y. Nayatani, et al., “Field Trials on Color Appearance of Chromatic Colors under Various Light Sources,” Color Res. Appl. 13 , 307-317 (1988)

43. M. D. Fairchild, “Color Appearance Models,” Addison-Wesley, Reading, (1998)

44. CIE TC1-34, “The CIE 1997 Interim Colour Appearance Model (Simple Version), CIECAM97s,” (Apr., 1998)

45. N. R. Draper, H. Smith, “Applied Regression Technique, Second Edition,” John Wiley & Sons (1996)

46. IEC/2CD 61966-3, “Colour measurement and management in multimedia systems and equipment, Part 3: Equipment using cathode ray tubes,” (1998)

47. R. W. G. Hunt, “Measuring Colour, Second Edition,” Ellis Horwood, London, 213-258 (1991)

48. G. A. Gescheider, “Psychophysics: Method, Theory, and Application, Second Edition,” Lawrence Erlbaum Associates, Publishers, Hillsdale, 151-154 (1985)

Naoya Katoh received his B. Eng. degree of precision mechanics in 1987 from Kyoto University, Japan. In the same year, he joined Sony Corporation where his main research focused on the development of the novel printing methods. He received MSc. degree of color science in 1997 from Rochester Institute of Technology, USA. He is now a senior research scientist at the Research Center, Sony Corporation, Tokyo. His current researches focus on the color image processing and the color appearance modeling through the different media. He is a member of the Society of Electrophotography, Japan and the Society for Imaging Science and Technology, and received IS&T's Charles E. Ives Award in 1994. He is involved in color management standardization activities of ICC, IEC/TC100/PT61966 and CIE. He also serves as a Technical Program Committe for the IS&T/SID's Color Imaging Conference.

Kiyotaka Nakabayashi received his master's degree of Computer Science and Information Mathematics in 1996 from the University of Electro-Communications, Japan. In the same year, he joined Sony Corporation where his main researches focused on the color image processing and the color appearance modeling through the different media. He is a member of the Color Science Association of Japan.

Masahiko Ito received BS and MS degrees in electrical engineering from Chiba University, Japan, in 1992 and 1994 respectively. He joined Sony Corporation in 1994. His main research interests are color image processing, particularly in developing novel algorithms for gamut mapping. He is a member of the Institute of Image Electronics Engineers of Japan.

Shin Ohno received his BS and Dr. Eng. degrees from Chiba University and Tokyo Institute of Technology in 1962 and 1979, respectively. In 1962, he entered the Technical Research Laboratories of NHK, Japan Broadcasting Corporation as a research associate. He has worked in the field of image recording systems and media for TV programs. Since 1980, he has studied the new TV application of video-hardcopy. In 1989 he entered the Electronic Photography Division of Sony Corporation. Now he is the Chief Engineer of Still Imaging Division, B&P Company of Sony Corporation. He is a guest professor of the graduate school, Chiba University. He is also a fellow of IS&T and a member of Board of Director Meeting.

Fig. 9 Images Used for the Visual Experiments

Fig. 10 Pixel Histogram of the Images in a*b* Coordinates

(Luminance Level 100 cd/m^2)

Adaptation Ratio 0%   Adaptation Ratio 60%   Adaptation Ratio 100%

Fig. 11 Hardcopy Output at Different Adaptation Ratio

(Adaptation Ratio 60%)

Luminance 100 cd/m^2 Luminance 200 cd/m^2 Luminance 300 cd/m^2

Fig. 12 Hardcopy Output at Different Luminance Levels

$$\overline{X'}_{(CRT)} = \frac{X'_{(CRT)}}{Y'_{n(CRT)}} = \frac{X_{(CRT)} + R_{bk}\ X_{(Ambient)}}{Y_{n(CRT)} + R_{bk}\ Y_{(Ambient)}}$$

$$\overline{Y'}_{(CRT)} = \frac{Y'_{(CRT)}}{Y'_{n(CRT)}} = \frac{Y_{(CRT)} + R_{bk}\ X_{(Ambient)}}{Y_{n(CRT)} + R_{bk}\ Y_{(Ambient)}}$$

$$\overline{Z'}_{(CRT)} = \frac{Z'_{(CRT)}}{Y'_{n(CRT)}} = \frac{Z_{(CRT)} + R_{bk}\ X_{(Ambient)}}{Y_{n(CRT)} + R_{bk}\ Y_{(Ambient)}} \quad (4)$$ 9

$$\begin{bmatrix} \overline{X'}_{(CRT)} \\ \overline{Y'}_{(CRT)} \\ \overline{Z'}_{(CRT)} \end{bmatrix} = \frac{1}{Y'_{n(CRT)}} \begin{bmatrix} X'_{(CRT)} \\ Y'_{(CRT)} \\ Z'_{(CRT)} \end{bmatrix} = \frac{1}{Y_{n(CRT)} + R_{bk}\ Y_{(Ambient)}} \left\{ \begin{bmatrix} X_{(CRT)} \\ Y_{(CRT)} \\ Z_{(CRT)} \end{bmatrix} + R_{bk} \begin{bmatrix} X_{(Ambient)} \\ Y_{(Ambient)} \\ Z_{(Ambient)} \end{bmatrix} \right\} \quad (5)$$ 9

$$\begin{bmatrix} \overline{L}_{(CRT)} \\ \overline{M}_{(CRT)} \\ \overline{S}_{(CRT)} \end{bmatrix} = \begin{bmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0000 \end{bmatrix}_E \begin{bmatrix} \overline{X'}_{(CRT)} \\ \overline{Y'}_{(CRT)} \\ \overline{Z'}_{(CRT)} \end{bmatrix} \quad (6)$$ 10

$$\overline{L'}_{n(CRT)} = \overline{L}_{n(CRT)} / p_L$$

$$\overline{M'}_{n(CRT)} = \overline{M}_{n(CRT)} / p_M$$

$$\overline{S'}_{n(CRT)} = \overline{S}_{n(CRT)} / p_S \quad (7)$$ 11

$$p_L = \left(1 + Y'^{1/3}_{n(CRT)} + l_E\right) / \left(1 + Y'^{1/3}_{n(CRT)} + 1/l_E\right)$$

$$p_M = \left(1 + Y'^{1/3}_{n(CRT)} + m_E\right) / \left(1 + Y'^{1/3}_{n(CRT)} + 1/m_E\right)$$

$$p_S = \left(1 + Y'^{1/3}_{n(CRT)} + s_E\right) / \left(1 + Y'^{1/3}_{n(CRT)} + 1/s_E\right) \quad (8)$$ 11

$$l_E = 3\ \overline{L}_{n(CRT)} / (\overline{L}_{n(CRT)} + \overline{M}_{n(CRT)} + \overline{S}_{n(CRT)})$$

$$m_E = 3\ \overline{M}_{n(CRT)} / (\overline{L}_{n(CRT)} + \overline{M}_{n(CRT)} + \overline{S}_{n(CRT)})$$

$$s_E = 3\ \overline{S}_{n(CRT)} / (\overline{L}_{n(CRT)} + \overline{M}_{n(CRT)} + \overline{S}_{n(CRT)}) \quad (9)$$ 11

$$\begin{bmatrix} \overline{L'}_{n(CRT)} \\ \overline{M'}_{n(CRT)} \\ \overline{S'}_{n(CRT)} \end{bmatrix} = \begin{bmatrix} 1/p_L & 0 & 0 \\ 0 & 1/p_M & 0 \\ 0 & 0 & 1/p_S \end{bmatrix} \begin{bmatrix} \overline{L}_{n(CRT)} \\ \overline{M}_{n(CRT)} \\ \overline{S}_{n(CRT)} \end{bmatrix} \quad (10)$$ 11

$$\overline{L''}_{n(CRT)} = R_{adp} \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \overline{L'}_{n(CRT)} + (1 - R_{adp}) \left(\frac{Y_{n(Ambient)}}{Y_{adp}}\right)^{1/3} \overline{L}_{n(Ambient)}$$

$$\overline{M''}_{n(CRT)} = R_{adp} \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \overline{M'}_{n(CRT)} + (1 - R_{adp}) \left(\frac{Y_{n(Ambient)}}{Y_{adp}}\right)^{1/3} \overline{M}_{n(Ambiebt)}$$

$$\overline{S''}_{n(CRT)} = R_{adp} \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \overline{S'}_{n(CRT)} + (1 - R_{adp}) \left(\frac{Y_{n(Ambient)}}{Y_{adp}}\right)^{1/3} \overline{S}_{n(Ambient)}$$

where $Y_{adp} = \left\{ R_{adp}\ Y'^{1/3}_{n(CRT)} + (1 - R_{adp})\ Y^{1/3}_{n(Ambient)} \right\}^3$ (11) 12

$$\overline{L''}_{n(CRT)} = R_{adp}\,\overline{L'}_{n(CRT)} + (1-R_{adp})\,\overline{L}_{n(Ambient)}$$

$$\overline{M''}_{n(CRT)} = R_{adp}\,\overline{M'}_{n(CRT)} + (1-R_{adp})\,\overline{M}_{n(Ambiebt)}$$

$$\overline{S''}_{n(CRT)} = R_{adp}\,\overline{S'}_{n(CRT)} + (1-R_{adp})\,\overline{S}_{n(Ambient)} \quad (12)$$ 13

$$L_S = \overline{L}_{(CRT)} / \overline{L''}_{n(CRT)}$$

$$M_S = \overline{M}_{(CRT)} / \overline{M''}_{n(CRT)}$$

$$S_S = \overline{S}_{(CRT)} / \overline{S''}_{n(CRT)} \quad (13)$$ 13

$$\begin{bmatrix} L_S \\ M_S \\ S_S \end{bmatrix} = \begin{bmatrix} 1/\overline{L''}_{n(CRT)} & 0 & 0 \\ 0 & 1/\overline{M''}_{n(CRT)} & 0 \\ 0 & 0 & 1/\overline{S''}_{n(CRT)} \end{bmatrix} \begin{bmatrix} \overline{L}_{(CRT)} \\ \overline{M}_{(CRT)} \\ \overline{S}_{(CRT)} \end{bmatrix} \quad (14)$$ 13

$$\begin{bmatrix} \overline{L}_{(Print)} \\ \overline{M}_{(Print)} \\ \overline{S}_{(Print)} \end{bmatrix} = \begin{bmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0000 \end{bmatrix}_E \begin{bmatrix} \overline{X}_{(Print)} \\ \overline{Y}_{(Print)} \\ \overline{Z}_{(Print)} \end{bmatrix} \quad (15)$$ 14

$$L_S = \overline{L}_{(Print)} / \overline{L}_{n(Print)}$$

$$M_S = \overline{M}_{(Print)} / \overline{M}_{n(Print)}$$

$$S_S = \overline{S}_{(Print)} / \overline{S}_{n(Print)} \quad (16)$$ 14

$$\begin{bmatrix} L_S \\ M_S \\ S_S \end{bmatrix} = \begin{bmatrix} 1/\overline{L}_{n(Print)} & 0 & 0 \\ 0 & 1/\overline{M}_{n(Print)} & 0 \\ 0 & 0 & 1/\overline{S}_{n(Print)} \end{bmatrix} \begin{bmatrix} \overline{L}_{(Print)} \\ \overline{M}_{(Print)} \\ \overline{S}_{(Print)} \end{bmatrix} \quad (17)$$ 14

$$\begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} = \begin{bmatrix} 1.9102 & -1.1122 & 0.2019 \\ 0.3709 & 0.6291 & 0.0000 \\ 0.0 & 0.0 & 1.0000 \end{bmatrix}_E \begin{bmatrix} L_S \\ M_S \\ S_S \end{bmatrix} \quad (18)$$ 14

$$L_S^* = 116\,(Y^S)^{1/3} - 16$$

$$a_S^* = 500\,\left\{(X_S)^{1/3} - (Y_S)^{1/3}\right\}$$

$$b_S^* = 200\,\left\{(Y_S)^{1/3} - (Z_S)^{1/3}\right\} \quad (19)$$ 15

$$C_S^* = \sqrt{(a_S^*)^2 - (b_S^*)^2}$$

$$h_S^\circ = \tan^{-1}\left(\frac{a_S^*}{b_S^*}\right) \quad (20)$$ 15

$$Y = 1.0 - \left[K_1 \exp(-X_1 t) + K_2 \exp(-X_2 t)\right] \quad (21)$$ 24