Appearance Match between Soft Copy and Hard Copy under Mixed Chromatic Adaptation

Naoya Katoh
Research Center, Sony Corporation, Tokyo, Japan

Abstract

Human visual system is partially adapted to the CRT monitor's white point and partially to the ambient light, when comparing a soft-copy image with the reproduced hard-copy image. The visual experiments were performed on the effect of the ambient lighting under mixed chromatic adaptation. It was found that human visual system is 40% to 60% adapted to CRT monitor's white point and the rest to the ambient light. This adaptation ratio itself was found to be independent of the luminance level of the ambient lighting for the portrait images.

Practical method for appearance match between soft-copy and hard-copy is presented in this paper. This method is fundamentally based on a simple von Kries' adaptation model and in addition, takes into account of the human visual system's "partial adaptation."

Introduction

CRT monitors are often used as a soft proofing device for the hard-copy image output. However, what the user sees on the monitor does not match its output, even if the monitor and the output device are calibrated with colorimetric values such as CIE/XYZ or CIE/L*a*b*. This is especially obvious when correlated color temperature (CCT) of CRT monitor's white point significantly differs from that of ambient light. In a typical office environment, one uses a computer graphic monitor having a CCT of 9300K in a room illuminated by white fluorescent light of 4150K CCT. Under such a viewing condition, it is assumed that human visual system is partially adapted to the CRT monitor's white point and partially to the ambient light.

In my first experiment[1], it was found that human visual system is 40% to 60% adapted to monitor's white point and the rest to the ambient light, when comparing the soft copy image with the hard copy image. It was also found that the adaptation ratio was independent of the chromaticity of the monitor's white point. The contrast difference between soft-copy image and hard-copy image caused by the reflection of the ambient light on the CRT screen was compensated by adding gamma to the soft-copy images. Since the white point's luminance of the soft-copy and the hard-copy were set to similar, the gamma was set to a constant of 1.25.

In my next experiment[2], another visual was performed to optimize this gamma at three different luminance levels. However, the gamma function was found to be insufficient to compensate for the contrast difference. One of the probable reason was that same gamma function was applied for all three channels. Since the reflection on the CRT screen is produced by the ambient light, black does not have same chromaticity as the white point of the CRT monitor. Optimizing gamma for each channel could have improved the model.

In this paper, there are two major modifications to my previous methods. First, the equations for calculating partially adapted white point was modified to adjust for the luminance level difference. Second, reflection of the ambient light on the CRT tube was taken into consideration.

Appearance Modeling

Appearance modeling in this method essentially consists of three stages: 1) compensation for difference between soft-copy image and hard-copy image, 2) transformation from tristimulus values to cone signals, and 3) chromatic adaptation compensation.

Contrast Compensation

First, the contrast difference between soft-copy image and hard-copy image must be compensated. An important effect of ambient lighting is the variation of the perceived image contrast in accordance with the surround's luminance level relative to the monitor's luminance. This contrast difference is mainly caused by the reflection of the ambient light on the CRT screen[3].

The black on the CRT screen will not be dark enough because the reflection of the ambient lighting 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 CIE/L*a*b* equations imply, the contrast of the soft copy 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 as an offset to the colors produced by the red, green and blue phosphors.

$$X'_{(CRT)} = X_{(CRT)} + R_{bk} \cdot X_{(Ambient)}$$
$$Y'_{(CRT)} = Y_{(CRT)} + R_{bk} \cdot Y_{(Ambient)} \qquad (1)$$
$$Z'_{(CRT)} = Z_{(CRT)} + R_{bk} \cdot Z_{(Ambient)}$$

where R_{bk} is the reflection ratio of the CRT screen surface, and the subscript *(CRT)* refers to the CRT monitor and *(Ambient)* refers to the surround luminance. After adding this reflection as an offset, maximum value of $Y'_{(CRT)}$ is normalized to 100.

Transformation From Tristimulus Values To Cone Signals

Then, the tristimulus values are transformed to raw cone signals. The Hunt-Pointer-Estevez transformation matrix normalized to equi-energy illuminant is used here, since it is desirable to normalize the cone signals for equality for the self-luminous colors[4].

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.0 & 0.0 & 1.0 \end{bmatrix}_E \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (2)$$

Chromatic Adaptation Compensation

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

The first step in the white 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, human visual system will not completely adapt to a CRT monitor's white point which is significantly different from D65 illuminant[5, 6]. Adaptation becomes less complete as the chromaticity of the adapting stimulus deviates from the D65 and as the luminance of the adapting stimulus decreases. The incomplete adaptation point: $L'_{n(CRT)}$, $M'_{n(CRT)}$, $S'_{n(CRT)}$, can be expressed as follows;

$$L'_{n(CRT)} = L_{n(CRT)} / p_L$$
$$M'_{n(CRT)} = M_{n(CRT)} / p_M \qquad (3)$$
$$S'_{n(CRT)} = S_{n(CRT)} / p_S$$

where, p_L, p_M, p_S are the chromatic adaptation factors used in Hunt appearance model[4].

$$p_L = \left(1 + Y_{mon}{}^{1/3} + l_E\right) / \left(1 + Y_{mon}{}^{1/3} + 1/l_E\right)$$
$$p_M = \left(1 + Y_{mon}{}^{1/3} + m_E\right) / \left(1 + Y_{mon}{}^{1/3} + 1/m_E\right)$$
$$p_S = \left(1 + Y_{mon}{}^{1/3} + s_E\right) / \left(1 + Y_{mon}{}^{1/3} + 1/s_E\right) \qquad (4)$$

$$l_E = 3 \cdot L_{n(CRT)} / (L_{n(CRT)} + M_{n(CRT)} + S_{n(CRT)})$$
$$m_E = 3 \cdot M_{n(CRT)} / (L_{n(CRT)} + M_{n(CRT)} + S_{n(CRT)})$$
$$s_E = 3 \cdot S_{n(CRT)} / (L_{n(CRT)} + M_{n(CRT)} + S_{n(CRT)}) \qquad (5)$$

where, Y_{mon} is the absolute luminance of the monitor's white point in this case.

The second step is compensation for mixed chromatic adaptation. In a typical office setting, soft copy 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 graphic monitor's 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 human visual system for soft copy images can be expressed as inter-mediate point of the two.

Newly defined adaptation point can be expressed as follows;

$$L''_{n(CRT)} = R_{adp} \cdot \left(\frac{Y_{mon}}{Y_{adp}}\right) \cdot L'_{n(CRT)} + (1 - R_{adp}) \cdot \left(\frac{Y_{sur}}{Y_{adp}}\right) \cdot L_{n(Ambient)}$$
$$M''_{n(CRT)} = R_{adp} \cdot \left(\frac{Y_{mon}}{Y_{adp}}\right) \cdot M'_{n(CRT)} + (1 - R_{adp}) \cdot \left(\frac{Y_{sur}}{Y_{adp}}\right) \cdot M_{n(Ambient)}$$
$$S''_{n(CRT)} = R_{adp} \cdot \left(\frac{Y_{mon}}{Y_{adp}}\right) \cdot S'_{n(CRT)} + (1 - R_{adp}) \cdot \left(\frac{Y_{sur}}{Y_{adp}}\right) \cdot S_{n(Ambient)} \qquad (6)$$

where $Y_{adp} = R_{adp} \cdot Y_{mon} + (1 - R_{adp}) \cdot Y_{sur}$

where, R_{adp} is the adaptation ratio to the monitor's white point, and Y_{sur} is the absolute luminance of the ambient light. When the ratio equals 1.0, human visual system is completely adapted to the monitor's white point and none to the ambient light. This case is conceptually close to the CIE/L*a*b* matching and the reproduced image will look much reddish. Conversely, when the ratio is 0.0, human visual system is totally adapted to the ambient light and none to the monitor's white. This case is conceptually close to the CIE/XYZ matching and the reproduced image will look much bluish.

In my first experiment[1], the luminance of the white point on the monitor and the white of the paper was set to nearly equal. In such a case, the weighting factors (Y_{mon}/Y_{adp},), (Y_{sur}/Y_{adp}) in above equations are reduced to the unity, therefore the same equations could still be used. Since the luminance of the two is different in this experiment, weighting factors were introduced.

Image Transformation

In this experiment, original soft-copy images on the monitor are reproduced to the hard-copy by the printer. The 21" TrinitronN™ monitor: Sony "GDM-2036" was used and its characterization was done by the method proposed by the Berns et. al.[8,9]. For the output device, continuous ink jet printer: Iris SmartJet™ 4012 was used. The printer was characterized by making 3D Look-up-table. The XYZ-to-CMY LUT was created by mathematical transformation from 9×9×9 color patch measurement[10].

Soft-copy image data is transformed to hard-copy image data as follows:

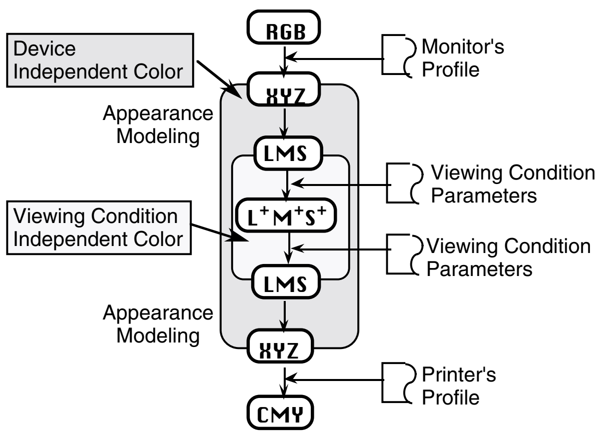

Figure 1. The Flow of Image Transformation

1) Device dependent signals (RGB) are transformed into device-independent color space (XYZ) through the monitor's profile. Then, the reflection of the ambient lighting on the CRT screen is added as an offset.

2) Tristimulus values (XYZ) are transformed to cone signals (LMS).

3) Then, the simple von Kries adaptation model is used to get the corresponding cone signals for the output image using viewing condition parameters. In this model, necessary viewing condition parameters are; (1) the chromaticity of the monitor's white point, source (2) Y_{mon}: the absolute luminance of the monitor's white point, (3) the chromaticity of the ambient light, and (4) Y_{sur}: the surround luminance for the input. For the output, only the tristimulus value of the paper white is necessary.

$$\begin{aligned} L_{(\mathrm{Pr\,int})}/L_{n,(\mathrm{Pr\,int})} &= L_{(CRT)}/L''_{n,(CRT)} = L^+ \\ M_{(\mathrm{Pr\,int})}/M_{n,(\mathrm{Pr\,int})} &= M_{(CRT)}/M''_{n,(CRT)} = M^+ \\ S_{(\mathrm{Pr\,int})}/S_{n,(\mathrm{Pr\,int})} &= S_{(CRT)}/S''_{n,(CRT)} = S^+ \end{aligned} \quad (7)$$

4) The cone signals (LMS) are then converted to tristimulus values (XYZ).

5) The tristimulus values (XYZ) are converted to device-dependent signals (CMY) for the ink jet printer through the printer's profile.

Visual Experiment

A visual experiment was performed to observe the best adaptation ratio: R_{adp} for the soft copy images at 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/m² and 297.8 cd/m², respectively. The absolute luminance of CRT monitor's white point was set to 99.8 cd/m², and its CCT was 9200K.

Three images (two portrait images and an image of macaws) were used for this visual experiment. The original image (1536 × 1024 pixels: RGB 8 bits) was displayed on the CRT screen at 72 dpi at a half of its size (267mm × 177mm) with small area of 100% white patches as a reference in the uniform gray background. Transformed hard-copy images through the procedure above were reproduced by the Iris SmartJet printer at the resolution of 150 dpi (256mm × 171mm).

Images at six levels of the soft copy adaptation ratio Radp (0, 20, 40, 60, 80, 100%) were reproduced and used for the paired comparison experiment. Fifteen pairs were formed from those six images. Before the experiment, observers were given a few minutes to adapt to the luminance level of the room. Observers were instructed to sit approximately 50-60 cm from the screen and to identify better matching hard-copy image to the original soft-copy image on the monitor from a given pair of hard copy images. Observers could move the pair of the images anywhere he/she desired, but not on the screen next to soft copy image. No time restriction was placed on the observers. Eighteen color-normal observers (16 male and 2 female: ages from 25 to 41) participated. Using Thrustone's law of comparative judgment, ordinal-scale visual decisions were converted to the interval psychometric scale.

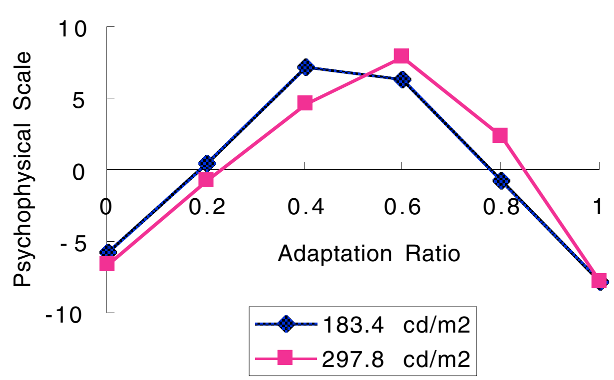

Figure 2.1. A Portrait Image

Result

Figures 2.1 below shows a result of psychophysical scale of matching versus adaptation ratio for a portrait image.

Since both of the portrait images showed similar trend, only one of them is shown here. The most preferred ones were images at 40% and 60% adaptation ratio, while images at the adaptation ratio of 0% and 100% had two of the worst scores. This implies that human visual system is adapted between 40% and 60% to the CRT monitor for both luminance levels.

Figures 2.2 shows a result of psychophysical scale of matching for an image of macaws. A different trend was found in this case. The preferred ones were images at the adaptation ratio of between 20% and 60%, but those scores do not have significant difference statistically. This means that matching became less perfect for this image.

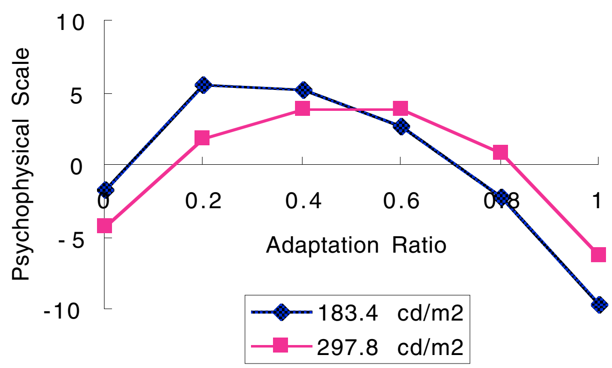

Figure 2.2. An Image of Macaws

Discussion

For the portrait images, it was found that best adaptation ratio was 40% to 60% even when the luminance levels differ from the monitor's luminance. However, for another image, matching became perfect when the luminance levels differ. The image of macaws has much more saturated colors than the portrait images used in this experiment. To make matching better for these saturated images, Hunt effect, i.e., increases in perceived colorfulness with increasing luminance must be taken into consideration.

$$\tilde{C} = \begin{bmatrix} 1 & c & c \\ c & 1 & c \\ c & c & 1 \end{bmatrix} \quad (8)$$

where c=0.219-0.0784 $\log_{10}(Y_n)$

The "C" matrix used to compensate for the Hunt effect in RLAB[7] was first applied to the image transformation. However, it was ignored in this experiment, because colors seemed to be de-saturated excessively by my subjective judgment.

The another phenomena was noticed through this experiment. Observers mentioned that colors in the soft-copy images appear darker than the colors in the reproduced hard-copy images. This is natural in absolute colorimetry. Human visual system no longer see monitor's white point as white but as bluish gray, when the surround luminance is much higher than the that of monitor's white point. The concept of partial adaptation must be applied not only for the chromaticity but also for the luminance.

Conclusion

Human visual system is 40% to 60% adapted to the monitor's white point and rest to the ambient light when comparing a soft-copy image compared to the hard-copy image. This adaptation ratio itself was found to be independent of the luminance level of the ambient lighting for the portrait images. However, for the saturated images this model still needs to be improved.

The reproduced hard-copy image at 60% and 40% adaptation ratio had acceptable matching to the original soft copy image on CRT. These appearance-matched images had much better reproduction than CIE/XYZ-matched or CIE/L*a*b*-matched images. Thus, this method can be used to improve soft copy color reproduction to match the hard copy color and vise-versa.

References

1. N. Katoh, "Practical Method for Appearance Match between Soft Copy and Hard Copy", *SPIE Publication* Vol. **2170**, 170-181, (1994).
2. N. Katoh, "Practical Method for Appearance Match between Soft Copy and Hard Copy (II)", Advance Printing of Papers "*Workshop ~ Electronic Photography "94 ~", STSPJ*, 55-58, (1994).
3. B. Saunders, "Visual Matching of Soft Copy and Hard Copy", *J. Imaging Tech*., Vol. **12**, 35-38, (1986).
4. R. W. G. Hunt, "Revised Colour-Appearance Model for Related and Unrelated Colours", *Color Res. Appl*., Vol. **16**, 146-165, (1991).
5. M. D. Fairchild, "Chromatic Adaptation to Image Displays", *TAGA Proc*., Vol. **2**, 803-823, Rochester, (1992).
6. M. D. Fairchild, "Formulation and Testing of an Incomplete-Chromatic-Adaptation Model", *Color Res. Appl*., Vol. **16**, 243-250, (1991).
7. M. D. Fairchild, R. S. Berns, "Image Color-Appearance Specification Through Extension of CIELAB", *Color Res. Appl*., Vol. **18**, 178-190, (1993).
8. R. S. Berns, R. J. Motta, M. E. Gorzynski, "CRT Colorimetry. Part I: Theory and Practice", *Color Res. Appl*., Vol. **18**, 299-314, (1993).
9. R. S. Berns, R. J. Motta, M. E. Gorzynski, "CRT Colorimetry. Part II: Metrology", *Color Res. Appl*., Vol. **18**, 315-325, (1993).
10. P. C. Hung, "Colorimetric Calibration in Electronic Imaging Devices Using Look-up-Table model and Interpolations", *J. Electronic Imaging*., Vol. **2**, 53-61, (1993).