Applying Mixed Adaptation to Various Chromatic Adaptation Transformation (CAT) Models

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Abstract

In 1998, a Technical Committee 8-04 was formed in CIE/Division 8, "*to investigate the state of adaptation of the visual system when comparing soft-copy images on self-luminous displays and hard copy images viewed under various ambient lighting conditions*." Several past studies indicated that applying mixed adaptation to the chromatic adaptation transformation improves the prediction of color appearance of CRT monitor viewed under mixed illumination. CIE/TC1-52 has been investigating the chromatic adaptation transforms. Most of the color appearance models in early 90's used Hunt-Pointer-Esteves (HPE) transformation. In late 90's, Luo et al.'s experimental results indicated that Bradford (BFD) transformation was superior, and BFD transformation was then adopted in CIECAM97s. Recently, Thornton suggested optimum RGB primaries are at 450-533-611nm. It was of great interest for the CIE/TC8-04 members to test other chromatic adaptation transformation in S-LMS mixed chromatic adaptation model, which originally uses HPE transformation. Above three color spaces were used in the visual experiments, along with XYZ and sRGB color spaces.

Experimental results indicated that BFD transform performed best, slightly followed by HPE transformation, when applied to S-LMS. It was also tested if the incomplete adaptation process was needed in mixed adaptation. RLAB method, D-factor used in CIECAM97s, and complete adaptation, were compared in S-LMS. RLAB method and D-factor resulted in much better score than complete adaptation, indicating that incomplete adaptation process is also important. According the results, revised model for the S-LMS, which is fully compatible with the revised CIECAM97s model, is proposed.

Introduction

Color imaging devices, such as DSCs (digital still cameras) and high quality color printers, are now readily available for consumers. However, many users still complain that color reproduction on hardcopy does not always match the original softcopy images, even with the help of CMSs (color management systems). There are many problems associated with this; device's stability, color characterization accuracy, and HVS(human visual system)'s chromatic adaptation.[1] This paper discusses about the last problem under the assumption that previous two are solved.

The effect of ambient light on color appearance of CRT has already been studied by several people. Brainard and Ishigami,[2] Choh, et al.,[3] and Oskoui and Pirrotta[4] used an achromatic color matching method (with uniform color patches) under a fixed state of chromatic adaptation. All of these experiments indicated the shift caused by the ambient illumination was subtle (10-20%). This could be mainly explained by the fact that the observers' eyes were fixated at the CRT screen in their experimental setup, thus the state of chromatic adaptation was more complete.

However, when users view pictorial images on the CRT screen and compares with the hardcopy reproduction under ambient lighting, HVS's adaptation is not fixed. Others who used pictorial images for cross-media color reproduction at mixed chromatic adaptation had much more adaptation shift. In Katoh's experiments,[1,5] softcopy images on the CRT screen were compared with the hardcopy image under an F6 illuminant. It was found that the HVS 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 and Choh[6] have also performed visual experiments for a cross-media comparison at a mixed state of chromatic adaptation. Their results were very similar to Katoh's previous experiments; an image with an adaptation shift of 50% was most preferred. Shiraiwa, et al.[7] tested mixed adaptation with their newly-proposed method under seven different illumination conditions. Their method includes a compensation for color rendering under different illuminants, which is very important for practical applications. Mixed adaptation was proved to be superior to conventional CMSs and as good as their proposed method, when CCT of the illuminant were different. Although the mixed adaptation was applied in CIE/xy coordinates, the adaptation ratio was 50-60%, which is also very similar to the previous studies. Henley and Fairchid[8] applied mixed adaptation to four different CATs (chromatic adaptation transforms), and tested them with six different matching methods. They used a 9x9 array of square patches on a white background. The incorporation of a mixed adaptation has improved the results in all conditions over the single adaptation (though the ratio was not specified in the paper). Its effectiveness was most notable at the simultaneous comparison, which is similar to others' experimental settings. For the simultaneous cross-media comparisons, since ones' eyes are not fixated, it could be assumed that the HVS is more affected by the ambient illumination than achromatic experiments that assumes fixated state of chromatic adaptation.

In 1998, a Technical Committee 8-04 was formed in CIE/Division 8 (Image Technology), "to investigate the state of adaptation of the visual system when comparing soft-copy images on self-luminous displays and hard copy images viewed under various ambient lighting conditions." http://www.colour.org/tc8-04/

On the other hand, CIE/TC1-52 has been investigating the chromatic adaptation transforms. Most of the color appearance models[9-11] until early 90's used Hunt-Pointer-Esteves (HPE) transformation. In late 90's, Luo et al.'s experimental results indicated that Bradford (BFD) transformation was superior,[12] and BFD transformation was then adopted in CIECAM97s.[13] This was developed by CIE/TC1-34 from combined efforts from all the CAM (color appearance model) proposals such as Hunt,[9] Nayatani,[10] RLAB,[11] LLAB,[12] etc.). Very recently, CIE/TC1-34 has submitted a report on "A Revision of CIECAM97s for Practical Applications."[14] In this report, the performance of the various chromatic adaptation transformation matrices was discussed. In CIECAM97s, BFD matrix with adaptation-level-dependent exponential non-linearity was used, which caused a problem for practical applications, as this calculation made CIECAM97s not invertable. Therefore, many of the current CMSs or color management applications are using so-called linear Bradford, which is simply using Bradford matrix without non-linear calculation.

It was of a great interest for the CIE/TC8-04 members to test other chromatic adaptation transformation in S-LMS mixed chromatic adaptation model,[1] which originally uses HPE transformation. The S-LMS is simply a chromatic adaptation model, which incorporates "mixed adaptation," and does not describe perceptual correlates as CAMs do. Most of CAMs can be separated into; 1) chromatic adaptation, 2) perceptual correlates, and 3) color differences. However, it should be noted that only the chromatic adaptation part of the CAMs is necessary for color matching for the cross-media reproduction that are viewed under "same" viewing conditions. (When one has to perform gamut mapping, the perceptual correlates and the color difference will be needed.)

S-LMS original model (primarily proposed in 1994) used HPE matrix for CAT, and Fairchild's (RLAB) model for incomplete adaptation. On the other hand, CIECAM97s used BFD matrix (with a non-linear calculation) for CAT, and D-factor for degree of adaptation (incomplete adaptation). Therefore, in this experiment, it was tested if S-LMS could be improved by applying CIE's recommendations on CAT and/or incomplete adaptation, or in other words, it was tested if incorporation of mixed adaptation to the CIECAM97s model is effective.

Original S-LMS Model (1998)

This section describes original S-LMS model proposed by Katoh[1] which are now under consideration in CIE/TC8-04. Chromatic adaptation modeling used in this model essentially consists of two stages, similar to the von Kries adaptation model; 1) transformation from tristimulus values to HVS's cone signals, and 2) compensation for chromatic adaptation. However, the reference white point to which the HVS adapts was investigated further.

First, tristimulus values are transformed into the HVS's cone signals. The Hunt-Pointer-Estevez transformation matrix normalized to an equi-energy illuminant is used.

$$\begin{bmatrix} L_{(CRT)} \\ M_{(CRT)} \\ S_{(CRT)} \end{bmatrix} = \begin{bmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0000 \end{bmatrix} \begin{bmatrix} X_{(CRT)} \\ Y_{(CRT)} \\ Z_{(CRT)} \end{bmatrix} \tag{1}$$

Then, compensation is made for the change in adaptation according to the surroundings. The HVS changes its cone sensitivity of each channel to get an image white-balanced as in color video cameras. Basically, the simple von Kries adaptation model is used, in which the signals of each channel are divided by the reference white's signals. There are two steps for the calculation of the adaptation white point; i.e., a) incomplete adaptation, and b) mixed adaptation.

a) **Incomplete Adaptation**

The first step in the adaptation point calculation is the compensation for the incomplete chromatic adaptation of the HVS for the self-luminous displays. Even if the monitor is placed in a totally dark room, the HVS'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. 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.[9]

$$\begin{aligned} L'_{n(CRT)} &= L_{n(CRT)} / p_L \\ M'_{n(CRT)} &= M_{n(CRT)} / p_M \\ S'_{n(CRT)} &= S_{n(CRT)} / p_S \end{aligned} \tag{2}$$

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

$$l_E = 3 \cdot L_{n(CRT)} / (L_{n(CRT)} + M_{n(CRT)} + S_{n(CRT)})$$
$$m_E = 3 \cdot M_{n(CRT)} / (L_{n(CRT)} + M_{n(CRT)} + S_{n(CRT)}) \qquad (4)$$
$$s_E = 3 \cdot S_{n(CRT)} / (L_{n(CRT)} + M_{n(CRT)} + S_{n(CRT)})$$

b) **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 4,000-5,000K. The CCT of the widely-used computer 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 HVS is partially adapted to the monitor's white point and rest to the ambient light's white point. Therefore, the adapting stimulus for the HVS 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.

$$L^n_{n(CRT)} = R_{adp} \cdot \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \cdot L'_{n(CRT)} + (1-R_{adp}) \cdot \left(\frac{Y_{(Ambient)}}{Y_{adp}}\right)^{1/3} \cdot L_{(Ambient)}$$
$$M^n_{n(CRT)} = R_{adp} \cdot \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \cdot M'_{n(CRT)} + (1-R_{adp}) \cdot \left(\frac{Y_{(Ambient)}}{Y_{adp}}\right)^{1/3} \cdot M_{(Ambient)} \qquad (5)$$
$$S^n_{n(CRT)} = R_{adp} \cdot \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \cdot S'_{n(CRT)} + (1-R_{adp}) \cdot \left(\frac{Y_{(Ambient)}}{Y_{adp}}\right)^{1/3} \cdot S_{(Ambient)}$$
$$\text{where } Y_{adp} = \left\{ R_{adp} \cdot Y'^{\,1/3}_{n(CRT)} + (1-R_{adp}) \cdot Y_{(Ambient)}^{1/3} \right\}$$

The weighting factors: $(Y_{n(CRT)}/Y_{adp})^{1/3}$, $(Y_{n(Ambient)}/Y_{adp})^{1/3}$ in equation (5) were introduced to correspond to the absolute luminance difference. When the luminance of the CRT: $Y_{n(CRT)}$ equals the ambient luminance: $Y_{n(Ambient)}$, equation (5) is reduced to the equation.

$$L^n_{n(CRT)} = R_{adp} \cdot L'_{n(CRT)} + (1-R_{adp}) \cdot L_{(Ambient)}$$
$$M^n_{n(CRT)} = R_{adp} \cdot M'_{n(CRT)} + (1-R_{adp}) \cdot M_{(Ambient)} \qquad (6)$$
$$S^n_{n(CRT)} = R_{adp} \cdot S'_{n(CRT)} + (1-R_{adp}) \cdot S_{(Ambient)}$$

When the ratio equals 1.0, the HVS 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 HVS 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 extreme cases assume that the HVS is at single-state chromatic adaptation. Most past studies indicated that adaptation ratio is 50-60%. This result could be verified by the Fairchild and Reniff's experiments on the time course of chromatic adaptation.[15] They found that the chromatic mechanisms were very rapid. According to their result, the HVS's adaptation reaches 60% very quickly in a few seconds, although it takes almost two minutes to reach 100% adaptation. Therefore, 60% is chosen for R_{adp} in the S-LMS model.

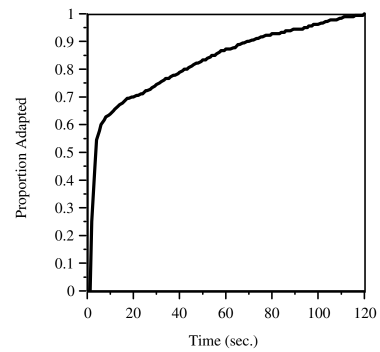

Figure 1. Time Course of Chromatic Adaptation [Fairchild]

With the newly-defined white points for the softcopy images, the von Kries chromatic adaptation model is applied. Thus, the viewing-condition independent index: S-LMS can be expressed as below.

$$L_S = L_{(CRT)} / L^n_{n(CRT)}$$
$$M_S = M_{(CRT)} / M^n_{n(CRT)} \qquad (7)$$
$$S_S = S_{(CRT)} / S^n_{n(CRT)}$$

For the hardcopy reproduction, the simple von Kries chromatic adaptation without 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. It should be noted, however, that reference white must be carefully chosen when paper white is not white enough.

$$L_S = L_{(\text{Print})} / L_{n(\text{Print})}$$
$$M_S = M_{(\text{Print})} / M_{n(\text{Print})} \qquad (8)$$
$$S_S = S_{(\text{Print})} / S_{n(\text{Print})}$$

Chromatic Adaptation Transformation (CAT) Matrices

Chromatic adaptation transform matrices listed below are compared in the experiment. HPE and BFD transforms are the ones that are used in CAMs, and has already been explained in earlier section. Recently, Thornton suggested optimum RGB primaries are at 450-533-611nm.[16] These three chromatic adaptation matrices were used in the visual experiments, along with XYZ and sRGB color spaces.[17]

BFD (Bradford) transform

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{9}$$

HPE (Hunt-Pointer-Esteves) transform

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0 & 0.0 & 1.0000 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{10}$$

Thornton's Optimal Primaries

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 1.8818 & -0.4094 & 0.3482 \\ -0.8130 & 1.6431 & 0.1190 \\ 0.0198 & -0.0405 & 0.9382 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{11}$$

sRGB Primaries

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & 0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{12}$$

As mentioned earlier, CIE/TC1-34 has recently published the report for CIECAM97s revision and proposed yet another CAT matrix. However, this matrix was not used in the experiment, since it was not available when the experiment was performed.

CIE's revised model

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.8562 & 0.3372 & -0.1934 \\ -0.8360 & 1.8324 & 0.0033 \\ 0.0357 & -0.0469 & 1.0112 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{13}$$

The matrix is very close to the BFD matrix, as shown in figure 2. This was derived as to be most compatible with current CIECAM97s. Therefore, we believe that this would produce very similar results to BFD, as we are dealing with much larger differences in our experiments.

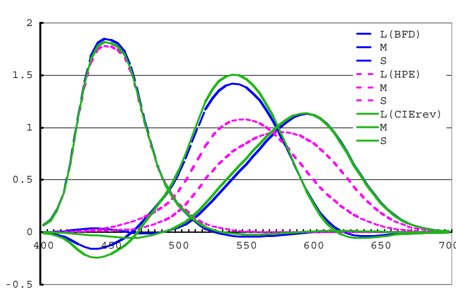

Figure 2. Cone Responses of HPE, BFD and revised CIE

Incomplete Adaptation Methods

It was also tested if the incomplete adaptation process was needed in the mixed adaptation model. Fairchild's method (used in RLAB), D-factor (used in CIECAM97s) and complete adaptation (i.e. no incomplete adaptation) were compared in the experiment.

In CIECAM97s, D-factor is used for the incomplete adaptation compensation. D-factor was originally proposed in LLAB model by Luo et al.[12] It is expressed as below (notation has been changed to S-LMS notation);

$$\begin{aligned} L'_{n(CRT)} &= \left[D\left(\frac{1}{L_{n(CRT)}}\right) + 1 - D \right] \cdot L_{(CRT)} = \frac{L_{(CRT)}}{1 \cdot D + L_{n(CRT)}(1-D)} \\ M'_{n(CRT)} &= \left[D\left(\frac{1}{M_{n(CRT)}}\right) + 1 - D \right] \cdot M_{(CRT)} = \frac{M_{(CRT)}}{1 \cdot D + M_{n(CRT)}(1-D)} \\ S'_{n(CRT)} &= \left[D\left(\frac{1}{S_{n(CRT)}}\right) + 1 - D \right] \cdot S_{(CRT)} = \frac{S_{(CRT)}}{1 \cdot D + S_{n(CRT)}(1-D)} \\ p &= (S_{(CRT)} / 1.0)^{0.0834} \\ D &= F - F / \left[1 + 2\left(Y_A^{1/4}\right) + \left(Y_A^2\right) / 300 \right] \end{aligned} \tag{14}$$

Y_A is the luminance of the adapting field, and F is a factor degree of adaptation (1.0 for average surround). And if we see the denominator in equation (14), which describes the HVS's adaptation point, incomplete adaptation point can be described as below with mathematical transformations.

$$\begin{aligned} L'_{n(CRT)} &= L_{n(CRT)} / d_L \\ M'_{n(CRT)} &= M_{n(CRT)} / d_M \\ S'_{n(CRT)} &= S_{n(CRT)}\big|^{p} / d_S \\ where\ p &= (S_{n(CRT)} / 1.0)^{0.0834} \end{aligned} \tag{15}$$

$$\begin{aligned} d_L &= D + L_{n(CRT)}(1-D) \\ d_M &= D + M_{n(CRT)}(1-D) \\ d_S &= D + S_{n(CRT)}\big|^{p}(1-D) \\ D &= F \cdot \left\{ 1 - 1 / \left[1 + 2\left(Y_A^{1/4}\right) + \left(Y_A^2\right) / 300 \right] \right\} \end{aligned} \tag{16}$$

As in Fairchild incomplete adaptation model used in S-LMS, adaptation becomes more complete as luminance increases. When D becomes zero, HVS is assumed to be adapted to illuminant E.

Experimental

The visual experiment was performed to find the best CAT matrix, and to find the best incomplete adaptation method. Seven different cases were considered. Five different CAT matrices described above (XYZ, BFD, HPE, Optimal, sRGB) were applied in S-LMS with RLAB incomplete adaptation method. In addition, two cases with a different incomplete adaptation with BFD matrix were tested. First, D-factor was applied in place of RLAB method. In this case, non-linearity for blue was also used, since this would be identical to "applying a mixed adaptation to CIECAM97s." For the last case, incomplete adaptation process was deleted. In all cases, mixed adaptation and incomplete adaptation process were applied only to softcopy side and not on hardcopy side.

Experimental procedures used in the experiments followed the guideline provided by the CIE/TC8-04 at;
http://www.colour.org/tc8-04/Experiment_guideline.html

Three images were used; party, portrait and picnic. Party and portrait are images of a lady shot indoor with grayish background, and picnic was an image of three ladies shot outdoor under blue sky. These images are also provided at;
http://www.colour.org/tc8-04/test_images/Sony/

Sony GDM-2000TC was used for displaying softcopy images. The GOGO model[18] which is an extension to CIE122[19] was used for the colorimetric characterization, and its accuracy was $\Delta E^*ab = 0.92 \pm 0.13$ (as average color difference ± standard deviation). Monitor's white point was set to CCT of 9,350K and luminance of 81.1 cd/m^2. The inkjet printer: Iris RealistFX was used for the hardcopy reproduction. The characterization was performed with 3D look-up-table, and its accuracy was $\Delta E^*ab = 1.24 \pm 0.11$.

The room was illuminated with a fluorescent lamp that was close to CIE/F10 (CCT=5,000K) lighting. A white paper set next to the monitor had a luminance of 72.7 cd/m^2. In our experiments, paper white was chosen as the reference white point for the hardcopy reproduction. An image displayed on the CRT screen was surrounded by 100% white proximal field of 5 mm wide in the 20% uniform gray background. There was a certain area of 100% white patches as a reference in addition to proximal field of the images.

Twenty color-normal observers participated. Before the experiment, observers were given approximately three minutes to adapt to the environment of the room. The observers sat approximately 50-60 cm from the screen. They were instructed to identify the better matching image to the original softcopy image from a given pair of reproductions. The simultaneous binocular (SMB) matching method was used. The observer could move the pair of images anywhere he/she desired, but not onto 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, ordinal-scale visual decisions were converted to the interval psychophysical scale.

Results and Discussions

Experimental results are shown in the figures 3 and 4. The result in figure 3 indicates that BFD transform performed the best, slightly followed by HPE, when applied to S-LMS mixed adaptation model. sRGB, on the other hand, performed worst for chromatic adaptation purpose. As our result indicated that BFD was most preferred, it is suggested that BFD can be replaced with HPE in the S-LMS model.

However, for different image contents, different trend was found. For the images party and portrait which contains large area of skin tones, XYZ performed as well as BFD, followed by HPE On the other hand, for image picnic which contains large area of blue sky, HPE performed the best followed by BFD and Thornton's optimal primaries. This indicates that different CAT transform performs better for different color regions. For skin tone, BFD (and XYZ) performed better than HPE, while HPE performed better than BFD (and Optimal) for blue sky.

As mentioned earlier, CIE is now revising CIECAM97s based on the latest research results. Therefore, from TC8-04 point of view, it would be wise to adopt whatever the TC1-34 recommends. Therefore, at this moment, the coice will be the CAT used in "revised" CIECAM97s.[14]

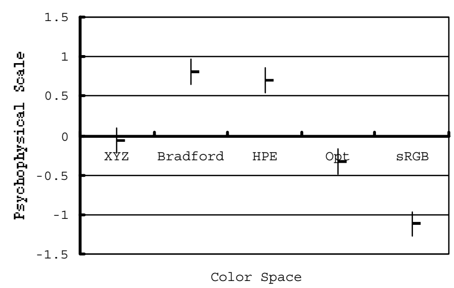

Figure 3. Comparison of Chromatic Adaptation Transformation

It was also tested if the incomplete adaptation process was needed in mixed adaptation model. RLAB method, D-factor used in CIECAM97s, and complete adaptation (i.e., no incomplete adaptation), were applied in S-LMS and compared. RLAB method and D-factor resulted in much better score than complete adaptation, indicating that incomplete adaptation process is also important. The result indicated that Fairchild's method was slightly better than the D-factor incomplete adaptation method. However, since the difference was subtle, it would be suggested that S-LMS incorporate the D-factor as CIE's recommendation.

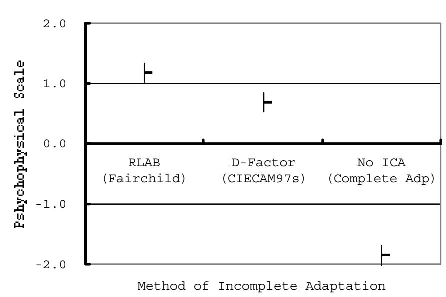

Figure 4. Comparison of Incomplete Adaptation Methods

Revised S-LMS Model (2001)

With these results, revised model for S-LMS is proposed. First, the CAT matrix described in CIE's proposed revision for CIECAM97s is used for chromatic adaptation transform.

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.8562 & 0.3372 & -0.1934 \\ -0.8360 & 1.8324 & 0.0033 \\ 0.0357 & -0.0469 & 1.0112 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{17}$$

Then, for the incomplete adaptation, D-factor is used. However, to apply mixed adaptation after this process, equations below are used which is mathematical identical to the CIE's proposal for incomplete adaptation.

$$\begin{aligned} L'_{n(CRT)} &= L_{n(CRT)} / d_L \\ M'_{n(CRT)} &= M_{n(CRT)} / d_M \\ S'_{n(CRT)} &= S_{n(CRT)} / d_S \end{aligned} \tag{18}$$

$$\begin{aligned} d_L &= D + L_{n(CRT)}(1-D) \\ d_M &= D + M_{n(CRT)}(1-D) \\ d_S &= D + S_{n(CRT)}\big|^{p}(1-D) \\ D &= F \cdot \left\{1 - 1/\left[1 + 2\left(Y_A^{1/4}\right) + \left(Y_A^2\right)/300\right]\right\} \end{aligned} \tag{19}$$

After the incomplete adaptation, mixed adaptation is applied, which is identical to equation (5).

$$\begin{aligned} L^n_{n(CRT)} &= R_{adp} \cdot \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \cdot L'_{n(CRT)} + (1-R_{adp}) \cdot \left(\frac{Y_{(Ambient)}}{Y_{adp}}\right)^{1/3} \cdot L_{(Ambient)} \\ M^n_{n(CRT)} &= R_{adp} \cdot \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \cdot M'_{n(CRT)} + (1-R_{adp}) \cdot \left(\frac{Y_{(Ambient)}}{Y_{adp}}\right)^{1/3} \cdot M_{(Ambient)} \\ S^n_{n(CRT)} &= R_{adp} \cdot \left(\frac{Y'_{n(CRT)}}{Y_{adp}}\right)^{1/3} \cdot S'_{n(CRT)} + (1-R_{adp}) \cdot \left(\frac{Y_{(Ambient)}}{Y_{adp}}\right)^{1/3} \cdot S_{(Ambient)} \end{aligned} \tag{18}$$

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

Finally, the viewing-condition independent index: S-LMS can be expressed as below.

$$\begin{aligned} L_S &= L_{(CRT)} / L^n_{n(CRT)} \\ M_S &= M_{(CRT)} / M^n_{n(CRT)} \\ S_S &= S_{(CRT)} / S^n_{n(CRT)} \end{aligned} \tag{19}$$

As in S-LMS model, incomplete adaptation and mixed adaptation only applies to the softcopy images. Simple von Kries Model is applied to the hardcopy images.

This model is now fully compatible with revised CIECAM97s, since it is simply incorporating mixed adaptation to the CIECAM97s when the softcopy and hardcopy images are simultaneously compared.

Conclusion

The chromatic adaptation methods were compared in S-LMS mixed adaptation model. Experimental results indicated that BFD transform performed best, slightly followed by HPE transformation, when applied to S-LMS. It was also tested if the incomplete adaptation process was needed in mixed adaptation model. RLAB method, D-factor used in CIECAM97s, and complete adaptation, were compared in S-LMS. RLAB method and D-factor resulted in much better score than complete adaptation, indicating that incomplete adaptation process is also important.

According the results, revised model for the S-LMS, which is fully compatible with the revised CIECAM97s model, is proposed. This is identical to incorporating mixed adaptation to the "revised" CIECAM97s.

References

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Biography

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