Spectral Based Color Correction Technique Compatible with Standard RGB System

Kunlaya Cherdhirunkorn[1], Norimichi Tsumura[1,2], Toshiya Nakaguchi[1] and Yoichi Miyake[1]

[1] Department of Information and Image Sciences, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

[2] PRESTO, Japan Science and Technology Corporation, 4-1-8 Honmachi, Kawaguchi-shi, Saitama 332-0012, Japan

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A spectral turn method is presented as a spectral based color correction method compatible with the standard RGB system by applying the idea of a multi-spectral method. The multi-spectral based color reproduction technique has been proposed for providing independent color of device and viewing conditions. However, it is difficult to replace the RGB devices with high cost multi-spectral devices since the latter have advanced only to the laboratory level. In the proposed method, the standard RGB values are converted into spectral information, then returned to RGB values for different viewing conditions. This process provides more accurate reproduction than the conventional forward process of the color reproduction. An experiment of psychophysical color matching was performed to evaluate the technique. The mixed chromatic adaptation model was applied to the method in the experiment, and the results showed the effectiveness of the proposed method.

Keywords: color reproduction, multi-spectral imaging, sRGB, E-commerce

1. Introduction

In the internet shopping or E-commerce system, the color of the image displayed on the computer monitor is thought to have important influence on a customer's decision of whether or not to purchase the product. However, in the present system, a customer cannot be sure if the color of actual product will be the same as that in the computer display, because appears differently under different viewing conditions.

The standard default color space for the internet, sRGB[1-2)] , has been widely used in computer operating systems, the internet, and the devices to provide accurate color matching. However, the viewing conditions of the sRGB system is not practical for the E-commerce system, since the sRGB color space is based on the monitor characteristics expected to be observed under illuminant D50. Although the devices used in the E-commerce system can be set to follow the sRGB references, most internet users cannot easily set the ambient illuminants to follow the sRGB reference viewing conditions. A color appearance model can be used to convert from tri-stimulus values to perceptual attributes, and used to achieve independent color of device and viewing conditions. In the E-commerce system, however, the tri-stimulus values under an arbitrary illuminant should be calculated before applying this color appearance model.

Multi-spectral imaging systems[3-11)] can reproduce highly accurate color under arbitrary illuminants; however, it will be hard to realize these practical systems to replace RGB imaging in the near future. Although multi-spectral imaging systems have developed rapidly in recent years, for example, multi-band cameras[12] and multi-primary displays[13], they are still in use at the laboratory level.

In this paper, an alternative spectral based color correction method compatible with the standard RGB system such as sRGB is proposed to reproduce accurate color under different viewing conditions. This technique assumes that the conventional sRGB based color reproduction has already been assured if it is under the standard sRGB viewing conditions. Based on multi-spectral based technology, the proposed method can compensate the reproduced color for the change of viewing conditions. We call this the spectral turn method (STM), since the standard RGB values are converted into spectral information and turned back into the RGB values for different viewing conditions. This “turned back” process is expected to provide more accurate color reproduction than the conventional forward process for color reproduction.

This paper is divided into three main sections. The next section shows the processes of the proposed spectral turn method (STM). In section 3, the accuracy of STM is evaluated using the image simulation technique. In section 4, we perform observer rating experiments to evaluate three color reproduction methods: multi-spectral, sRGB color reproduction and the proposed method under 4 kinds of lighting conditions. The mixed chromatic adaptation model, revised S-LMS model[14-15], is applied in STM for practical use when comparing the reproduced color under mixed illumination conditions.

2. Spectral Turn Method (STM)

Figure 1 shows the process of the proposed STM. We define the camera which is set based on sRGB color space as the sRGB camera, and the 3-primary display which is calibrated based on sRGB color space. Two types of color matching are assumed under the standard sRGB viewing conditions as conventional sRGB based color reproduction. The general sRGB camera is manufactured as two types to meet the two purposes. The sRGB camera used in case #1 in Fig. 1 was manufactured for processing the image to show on the sRGB display and to match the color appearance of the object under the light source *L#1* where the image was taken. In case #2) in the same figure, the sRGB camera was manufactured for processing the image to show on the sRGB display and to especially match the color appearance of the object under the sRGB reference viewing conditions. The second case is the same situation as the first when the light source *L#1* is set to D50 which is defined in sRGB standard viewing conditions. In this paper, we set *L#1* to D50 in the experiments for ease of evaluateing the proposed technique.

2.1 Assumed image processing algorithm in the camera

The image processing algorithm in the digital camera is not available to consumers. However, we can assume this algorithm in the sRGB camera achieves the above color match as follows. The image processing inside in the image acquisition part of the camera is assumed to be the process surrounded by broken lines in Fig. 1. When an image is taken, the reflectance spectra ($\boldsymbol{r} = [r(\lambda_{380}), r(\lambda_{390}), \ldots, r(\lambda_{780})]^t$) of the observed object travel into the camera, and are believed to be converted into XYZ tristimulus values ($\boldsymbol{x} = [X,Y,Z]^t$) under the light source L#1 to achieve the color matching case#1, where $[\ ]^t$ indicates a transposeing operation for the matrix or vector. This process can be written as follows[16].

$$\boldsymbol{x} = TL_1\boldsymbol{r} \tag{1}$$

where x is the vector of XYZ tristimulus values, L_1 is the diagonal matrix with spectral radiance of illuminant *L#1*. The matrix T is the matrix of the color matching function as

$$T = k\begin{bmatrix} \bar{x}(\lambda_{380}) & \bar{x}(\lambda_{390}) & \cdots & \bar{x}(\lambda_{780}) \\ \bar{y}(\lambda_{380}) & \bar{y}(\lambda_{390}) & \cdots & \bar{y}(\lambda_{780}) \\ \bar{z}(\lambda_{380}) & \bar{z}(\lambda_{390}) & \cdots & \bar{z}(\lambda_{780}) \end{bmatrix}; \qquad k = 100 / L_i\bar{y} \tag{2}$$

where k is the constant for normalization.

After the XYZ tristimulus values are obtained from the above equations, they are transformed to the XYZ values compatible with the adaptation of the human visual system by using the chromatic adaptation and color appearance transformation. Use of the sRGB reference color appearance model (CIECAM97s[17]) is assumed here. The gamut mapping is applied in the viewing independent color space in this transformation process. These XYZ values are transformed to RGB tristimulus values and finally to sRGB pixel values to show on the 3-primary display. The sRGB digital encodings for calculating from XYZ tristimulus values to the pixel values can be found in references[1, 2]. Finally, the color appearance of an object under illuminant *L#1* can be reproduced on the sRGB display in the sRGB viewing environment.

To achieve color matching case #2 in Fig. 1, spectral radiance L_1 in Eq. (1) and in the chromatic adaptation and color appearance transformation should be changed to D50 which is used in sRGB reference viewing conditions.

2.2 Spectral turn process

Based on the above assumed image processing inside the camera, we proposed use of the spectral turn process to obtain accurate color matching under the other illuminants (*L#2*). In the first step of this process, we compute the color inversely from the sRGB pixel values to the XYZ tristimulus values $\boldsymbol{x}$ under illuminant #1 based on the assumed image processing inside the camera. Since the chromatic adaptation and color appearance transformation are assumed to be embedded in the image processing of the camera, it is necessary to calculate this transformation inversely in this step.

In the second step, the obtained XYZ tristimulus values are inversely transformed to spectral reflectance of the object ($\boldsymbol{r} = [r(\lambda_{380}), r(\lambda_{390}), \ldots, r(\lambda_{780})]^t$). However, this is not invertible since data of the spectral reflectance has a higher dimension than tristimulus values. Therefore, here, we used the multiple regression estimation method[18] to allow this inversion. The 24 colors of the GretagMacbeth Color Checker were used as samples for this method as the preliminary experiments. These colors are known to be typical of colors in usual scenes. The 24 colors are large enough for regression in three variables for R, G, and B. Therefore, throughout this paper, we used the GretagMacbeth Color Checker to evaluate the proposed method

The estimation matrix G can be calculated by the following equation:

$$G = RX^t(XX^t)^{-1}, \tag{3}$$

$$X = [\boldsymbol{x}_1, \boldsymbol{x}_2, \ldots, \boldsymbol{x}_n], \quad R = [\boldsymbol{r}_1, \boldsymbol{r}_2, \ldots, \boldsymbol{r}_n],$$

where the matrix R represents the matrix of previously measured spectral reflectance of n samples. In this paper, n is 24 for the GretagMacbeth Color Checker. The spectral reflectance of each sample is represented by $\boldsymbol{r}_i$. The matrix X is the matrix of XYZ tristimulus values of n samplesm and these tristimulus values of each sample $\boldsymbol{x}_i$ can be calculated from Eq. (1). The spectral reflectance vector of the observed object can be estimated using this estimation matrix G from the vector of the XYZ tristimulus values $\boldsymbol{x}$ under illuminant #1,

$$\boldsymbol{r} = G\boldsymbol{x} \tag{4}$$

In the final step of STM, the estimated spectral reflectance of the object is turned back into sRGB pixel values to accurately match the reproduced color with the color of the original object under illuminant *#2* using the same process as the assumed image processing inside the camera. However, it is noted that L_1 in eq. (1) is changed to L_2, and that chromatic adaptation and color appearance transformation based on illuminant #2 is used in the process.

In the next section, the accuracy of the STM is investigated and evaluated based on computer simulations without considering the chromatic adaptation or color appearance transformation.

3. Evaluation of STM by Computer Simulation

Using simulation techniques, we looked into whether STM can be used to reproduce accurate color as well as the highly accurate multi-spectral based color reproduction method (MSM). Without using the image acquisition or real input-output devices in the simulation process, we could avoid the device noise of the multi-spectral imaging system. In the simulation, we were not concerned about the chromatic adaptation or the color appearance transformation in the STM process, since psychophysical judgments are not possible in such an evaluation by computer simulation.

We simulated 24 colors on the GretagMacbeth Color Checker Chart for 22 kinds of light source using the sRGB method, MSM and the proposed STM. These light sources were 6 CIE standard illuminants, 6 kinds of normal type, 3 kinds of broadband type and 3 kinds of three-band type representative fluorescent lights, and 4 kinds of commercially available three-band type fluorescent lamps.

In this simulation, we assumed that all of the reflectance spectra were estimated accurately in MSM. Therefore, we just calculated the XYZ tristimulus values of each color under each illuminant from the vector of the previously measured reflectance spectra of the Gretag Macbeth Color Checker Chart based on eq. (1). The sRGB pixel values for the display were calculated from the XYZ tristimulus values by following the assumed image processing of the sRGB camera without the chromatic adaptation or the color appearance transformation part. The XYZ tristimulus values under the D50 illuminant were used to calculate the sRGB pixel values for the sRGB method. For the simulation by STM, the spectral turn process was applied to the sRGB pixel values of the sRGB method to exchange illuminants from D50 to each of the 22 illuminants.

Figure 2 shows the simulated colors reproduced for the 22 illuminants by MSM (to the left of each color swatch), and the simulated colors reproduced by the sRGB method (to the right of each swatch). Figure 3 shows color swatches simulated using MSM and STM. Each pair of each color swatch in Fig. 2 is perceptibly different except for the swatch of the D50 illuminant, while almost all of the color pairs are similar.

In Figure 4, each color pair from Figs. 2 and 3 is compared by the average color difference values (ΔE94) under each illuminant with 2 degree viewing conditions. The dashed line shows ΔE94 is equal to 3, and it is said that the color pair is perceptibly different when the color difference values are above this threshold. The average ΔE94 in Fig. 4 shows that at the sRGB defined light source (Standard CIE D50), the sRGB method and STM provide the same color as MSM. The sRGB method can achieve acceptably identical color reproduction only for the D50 and D55 illuminants. The average ΔE94 values between MSM and STM are lower than the threshold of perceptibility for almost all light sources except the 3-band type of representative fluorescent lamp (F10, F11 and F12). This means that STM can provide similar colors calculated from the MSM for most light sources. STM can provide lower average color difference values than the sRGB method for all 22 light sources. These results indicate that STM can achieve more accurate color reproduction than the sRGB method for several illuminants.

In the next section, we describe visual comparison made to evaluate the proposed STM. The mixed chromatic adaptation model (the revised S-LMS model) was applied to the spectral turn process to enable visual comparison under the actual viewing conditions of internet shopping.

4. Evaluation of STM by Visual Comparison

In practice, color comparison in the internet shopping system is done under mixed illumination conditions between the color of the image displayed on the monitor and the color of the observed object. These conditions are generally composed of two main light sources, the self luminous display and the ambient light. In this section, STM was improved to be more practical for these conditions by applying the mixed chromatic adaptation model to the chromatic adaptation and color appearance transformation part of the process.

Here, we chose the revised S-LMS model, the mixed chromatic adaptation model proposed by Katoh and Nakabayashi in 2001[14)] and described further by Katoh in 2002[15)] , since it is compatibile with the revised CIECAM97s[17] used in the sRGB system. The revised S-LMS model is composed of three essential stages. In the first stage, the contrast variation of the softcopy images caused by reflection of the ambient light must be compensated. The second stage is the transformation from the contrast compensated XYZ tristimulus values to cone signals, and the final stage is the compensation for incomplete adaptation and mixed chromatic adaptation. Details of the model and calculation method can be found in references [13-14)].

4.1 Observer rating experiments

The observer rating experiments were performed by checking whether the developed practical STM could improve the accuracy of reproduced color by comparing it with the sRGB method and the highly accurate MSM (Fig. 5).

(1) Image Preparations

The GretagMacbeth Color Checker Chart was used as an observed object for these experiments. In the sRGB color reproduction, the original image of the observed object was photographed under 5500K cool white light (*L#1*) by a Nikon D1X digital RGB camera. The color mode for recording digital photographs of this camera was the sRGB mode. The white balance was set as the perfect white diffuser under the cool white light before taking pictures. The original image was transformed by the process of STM using the revised S-LMS model to correct the color to accurately match that of the objects under different ambient light (*L#2*).

The 5-band images of the GretagMacbeth Color Checker Chart for MSM were taken under tungsten light by a 5-band digital camera developed by Sugiura et al.[12)] Those images were used to estimate the spectral reflectance of the original object by applying the Wiener estimation method[19]. The average color difference $\Delta E94$ in MSM was 2.1 under D65 illuminant for 24 chips in the GretagMacbeth color checker. The estimated spectral reflectance was transformed to the XYZ values under different ambient light (*L#2*). Note that in the MSM, the revised S-LMS model was also used in the process for compatibility under the mixed illumination conditions. Each color patch of all images was checked to learn whether it was located inside the sRGB gamut area (in-gamut color).

(2) Viewing Conditions

Four kinds of commercially available three-band type fluorescent lamps, with a color temperature of 3000K, 3500K, 5000K, or 6700K, were used as the ambient lights (*L#2*) to imitate four typical office or home environments. For example, low color temperature lamps of 3000K or 3500K are usually used for room lighting in USA, Canada and Europe, while daylight (5000K) and cool white (6700K) lamps are more popular in Asia. The luminance level of the ambient lights was set at 300 lux. A standard CRT monitor (Barco Reference Calibrator V) calibrated based on the sRGB system was used to display each image in the experiments.

Under each ambient light, the images reproduced by STM and MSM for that illuminant and the original image were displayed at 72-dpi resolution with the same physical size as the GretagMacbeth Color Checker Chart in random order. Each softcopy image displayed on the middle of a uniform gray background (20% luminance factor against the monitor white point) was surrounded by the monitor’s 5 mm wide white stripe. The original GretagMacbeth Color Checker Chart was also surrounded by a 5 mm white border against a uniform gray cardboard with 20% luminance factor against the white paper.

(3) Subjective evaluation

Each color patch of the GretagMacbeth Color Checker Chart was compared to the image on the sRGB monitor using the simultaneous binocular matching method (SMB). This method simulates the real viewing situation when the customer uses both his/her eyes simultaneously to compare the color of image on the monitor with the delivered product.

Fifteen observers participated in the color matching under each viewing condition, after taking a test to confirm that they had normal color vision. The observers were given approximately two minutes to adapt to the viewing conditions of the room and were instructed to sit approximately 50-60 cm away from the monitor. They were instructed to judge the color similarity between each color patch and image on the monitor by a subjective rating (ranking order). A 5-level score evaluation was utilized to rate the similarity score, and scores were categorized from 1 to 5 as in Table 1.

To check the accuracy of the conventional sRGB method, color matching between the original image and the observed object under the sRGB reference viewing condition was also performed in the experiments

4.2 Results

The original image and the reproduced images from MSM and STM for 4 viewing conditions are shown in Figs. 6(a), 6(b), and 6(c), respectively. The color patch numbers are shown at upper right in the figure. By checking whether each color of the images reproduced from the three methods was in the sRGB gamut, we found that 8 colors reproduced by STM were not in the gamut (out-of-gamut) as shown in Table 2.

Figure 7 and Table 3 show the overall average and standard deviation of similarity scores of the three methods for 16 in-gamut colors viewed under the 4 light sources. The average and standard deviation was calculated from the results of the fifteen observers. The results indicated that STM performed better than the sRGB method for every light source and performed as well as the MSN under 3000, 3500 and 5000 K lighting conditions. For the 6700 K lighting, STM performed slightly better MSM. When we compared among the 4 light sources, the average similarity scores of STM and MSM were almost equal under every viewing condition. We determined that both these techniques can be used to reproduce color which is independent of viewing conditions On the other hand, the sRGB method provided color which is dependent on viewing conditions, since it gave the highest average scores only in 5000 K light source and had the worst results when the lighting condition was other than that. This is because the sRGB method was developed for accurate color matching under only sRGB reference viewing conditions; for other lighting conditions, the sRGB color could not be matched accurately to the original object.

When we also included the out-of-gamut colors, results of the 3 methods were shown in Fig. 8 and Table 4. Trend of the results of each method was similar to the those in Fig. 7 which combined only 16 in-gamut colors. These implied that the out-of-gamut colors did not much affect the results of any of the 3 methods in these experiments, and caused the average scores and standard deviation of the methods to change only slightly. The error bars of standard deviation values (STD) in Fig. 7 and Fig.

8 show that there was good color matching agreement among the 15 observers, since their average similarity scores for each light source were all within a single score range.

Figure 9 and Table 5 show the observers' combined performance of the sRGB method under the sRGB reference viewing conditions. The method gave average similarity scores of more than 3 for 19 colors for 24 of the Gretag Macbeth Colors. The colors in black and white mode (color numbers 19 to 24), which are the most important colors for color reproduction, were above 4. In Table 5, the average similarity scores combined from the 24 colors and the 15 observers is 3.46, which is higher than the average overall scores of the sRGB method under other viewing conditions shown in Fig. 7 and Fig. 8. These results confirmed that this method reproduced color accurately for the defined sRGB viewing conditions, but not for other conditions. We conclude that STM should be used instead of conventional RGB imaging, since STM is successfully achieves accurate color matching.

5. Conclusions and Discussion

An alternative spectral based color correction method compatible with sRGB color space, called the spectral turn method (STM), was introduced to solve the color mismatch problem in the E-commerce system. The accuracy of STM was preliminarily evaluated by computer simulation. The resultant color difference values indicated that STM could provide as accurate color as MSM and more accurate color than the sRGB color reproduction method in the 24 samples of GretagMacbeth color checkers. This advantage of STM over sRGB is due to the consideration of illuminant changes. STM was developed further for observer rating comparison under mixed illumination conditions by applying the mixed chromatic adaptation model, the revised S-LMS model. The reproduced color obtained by 3 methods (MSM, sRGB, and STM) had been visually compared to the original object under 4 kinds of representative real lighting conditions. The results of observer rating experiments had clearly shown that STM can be used to reproduce more accurate color than the sRGB color reproduction method for all lighting conditions in the 24 samples of GretagMacbeth color checkers. It provided color as accurate as the MSM, and is more practical for the E-commerce system, since it uses the conventional sRGB system instead of a multi-band camera which is not yet available on the market. In order to achieve the greatest advantage of STM, it is necessary to find a simple way to obtain the spectral radiance of illuminants under the viewing conditions of each internet user.

The proposed method (STM) provided acceptable color transformation for 24 chips in the Gretag Macbeth color checker for various changes of illuminant. However, the technique has a heoretical limitation compared to MSM:it gave the same values for metameric pairs in a 3 band system but not in a multi-band system. The color checker cannot be used to evaluate the metameric pairs. Further research is necessary to evaluate this limitation using a larger number of samples.

In the computer simulation, the results in Figure 4 showed that MSM is more advantageous than STM. In the visual comparison, however, the results in Figures 7, and 8 showed that there was no advantage of MSM over STM for the 24 chips in the Gretag Macbeth color checker. There may be two reasons for these results. The first is that we used only a small number of color chips, and the average color difference $\Delta E94$ in MSM was 2.1. This difference was not sufficiently smaller than the color difference between MSM and STM in the simulated experiment in Figure 4. Second, we believe that calibration errors accumulated in the MSM, since it was necessary to calibrate the multi-band camera, color appearance model, and display. In the STM, only the sRGB display is accurately calibrated to reproduce accurate color under the sRGB references as shown in Figure 9. Processes of the camera system and the color appearance model operate both backward and forward. The calibration errors may be cancelled in these backward and forward processes.

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Figure Caption

Figure 1 Process of the spectral turn method (STM).

Figure 2 Simulated color reproduced for 22 illuminants by MSM (to the left of each color swatch) and the simulated color reproduced by sRGB method (to the right of each color swatch).

Figure 3 Simulated color reproduced 22 illuminants by MSM (to the left of each color swatch) and the simulated color reproduced by STM (to the right of each color swatch) for 22 illuminants.

Figure 4 Average color difference values (E94) calculated from the simulated color pairs by sRGB method compared with MSM and STM compared with MSM for 22 illuminants.

Figure 5 Procedure of observer rating experiment for comparison among sRGB method, MSM and STM.

Figure 6 Reproduced images for 4 viewing conditions from sRGB color reproduction, MSM and STM.

Figure 7 Average overall performances of three methods for 16 in-gamut colors viewed under the 4 light sources. Average calculated from the results of 15 observers.

Figure 8 Average overall performances of three methods for all colors of Gretag Macbeth Color Checker Chart viewed under the 4 light sources. Average calculated from the results of 15 observers.

Figure 9 Performance of the sRGB method under the sRGB standard reference viewing condition (D50, 64Lux).

Table Captions

Table 1 Overall similarity scores

Table 2 The out-of-gamut colors (the colors which have RGB tristimulus values located outside the sRGB gamut area) from the images reproduced by STM for 4 viewing conditions

Table 3 Average and standard deviation values of similarity scores of three methods for 16 in-gamut colors viewed under the 4 light sources. The average and standard deviation values calculated from the results of 15 observers

Table 4 Average and standard deviation values of similarity scores of three methods for all 24 colors of Gretag Macbeth Color Checker Chart viewed under the 4 light sources. The average and standard deviation values calculated from the results of 15 observers

Table 5 Average and standard deviation values of similarity scores of sRGB method under the sRGB standard reference viewing condition (D50, 64Lux)

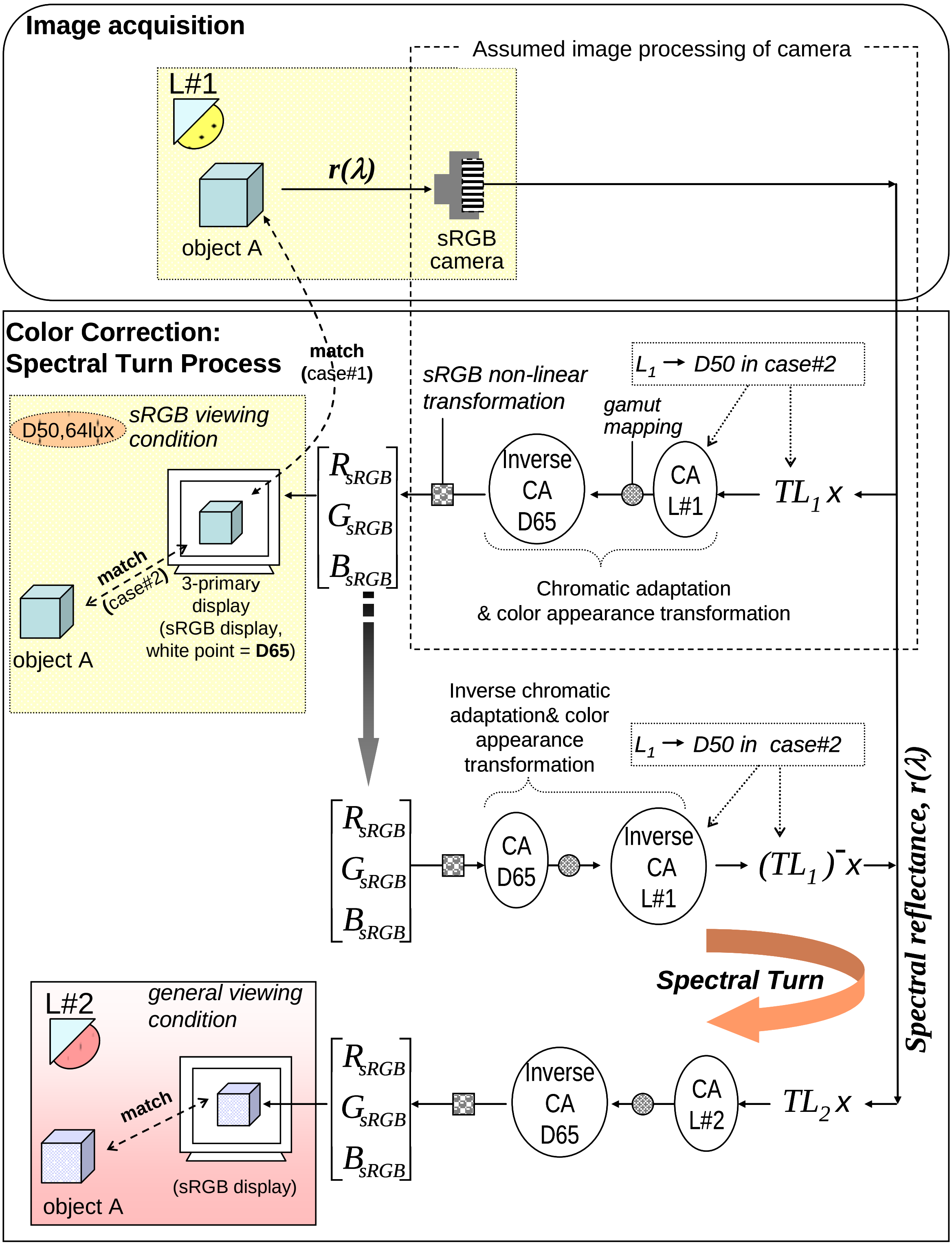

Figure 1 Process of the spectral turn method (STM).

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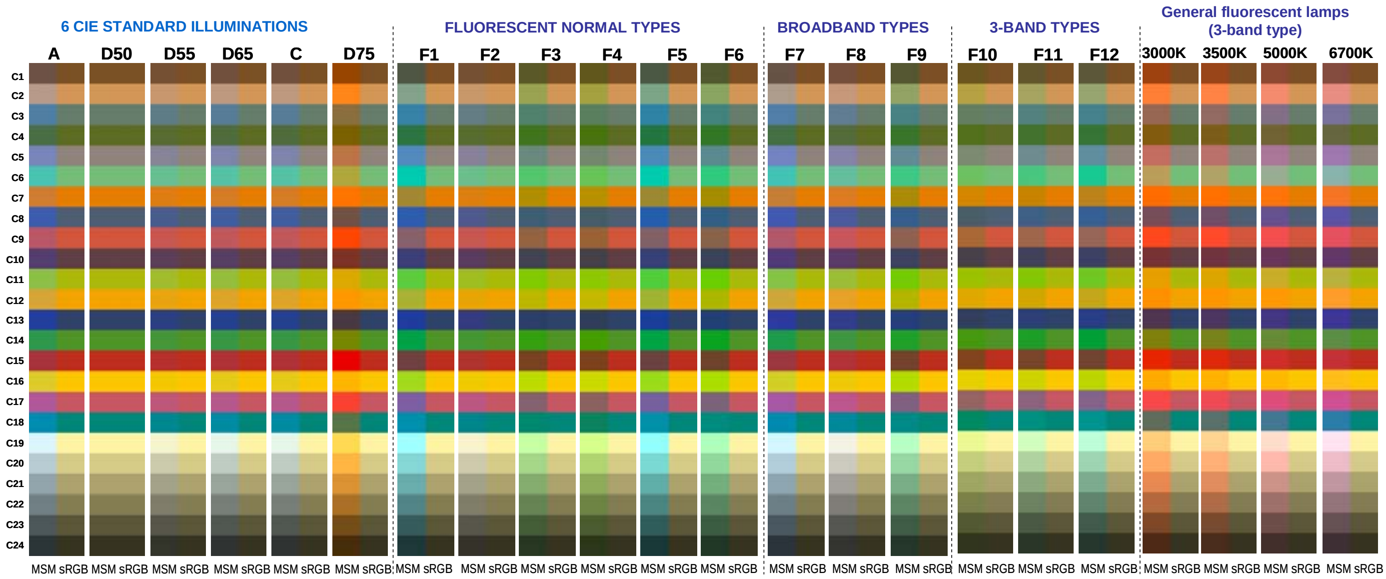

Figure 2 Simulated color reproduced for 22 illuminants by MSM (to the left of each color swatch) and the simulated color reproduced by sRGB method (to the right of each color swatch).

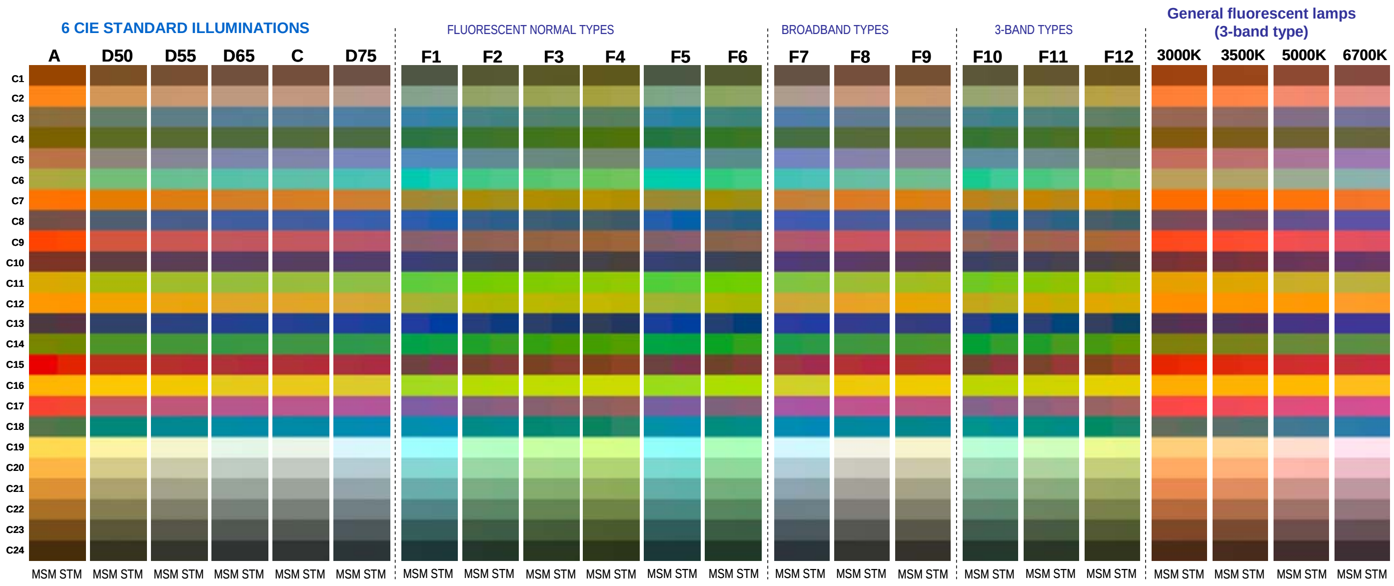

Figure 3 Simulated color reproduced 22 illuminants by MSM (to the left of each color swatch) and the simulated color reproduced by STM (to the right of each color swatch) for 22 illuminants.

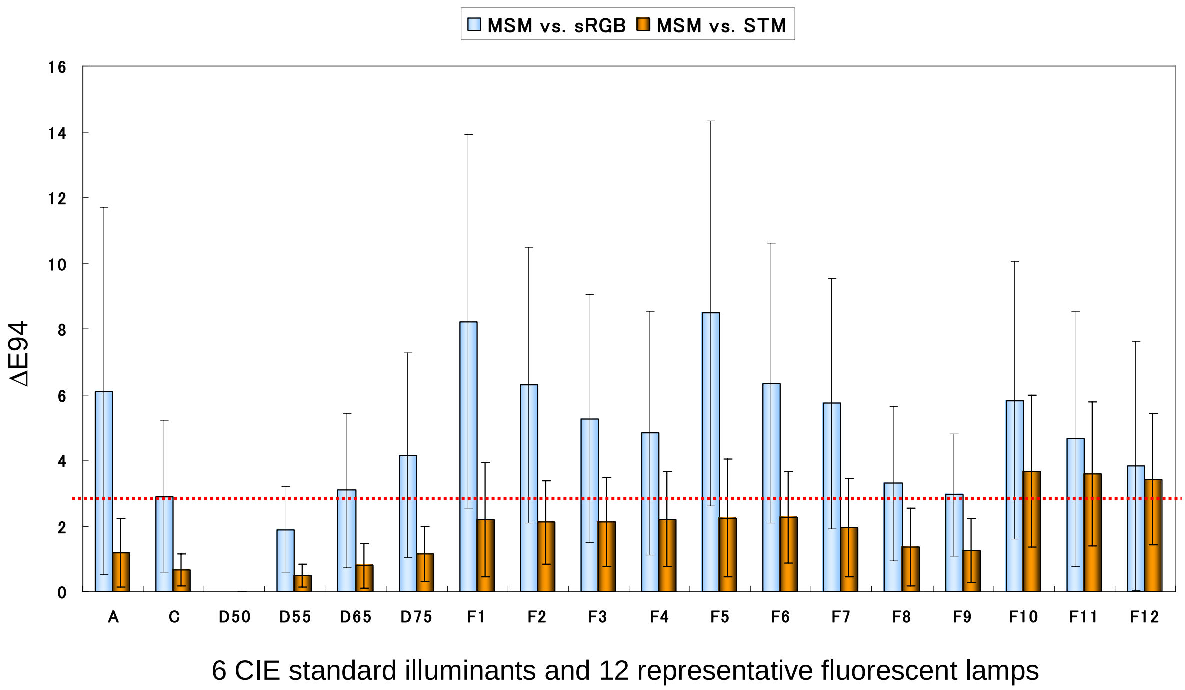

Figure 4 Average color difference values ($\Delta E94$) calculated from the simulated color pairs by sRGB method compared with MSM and STM compared with MSM for 22 illuminants.

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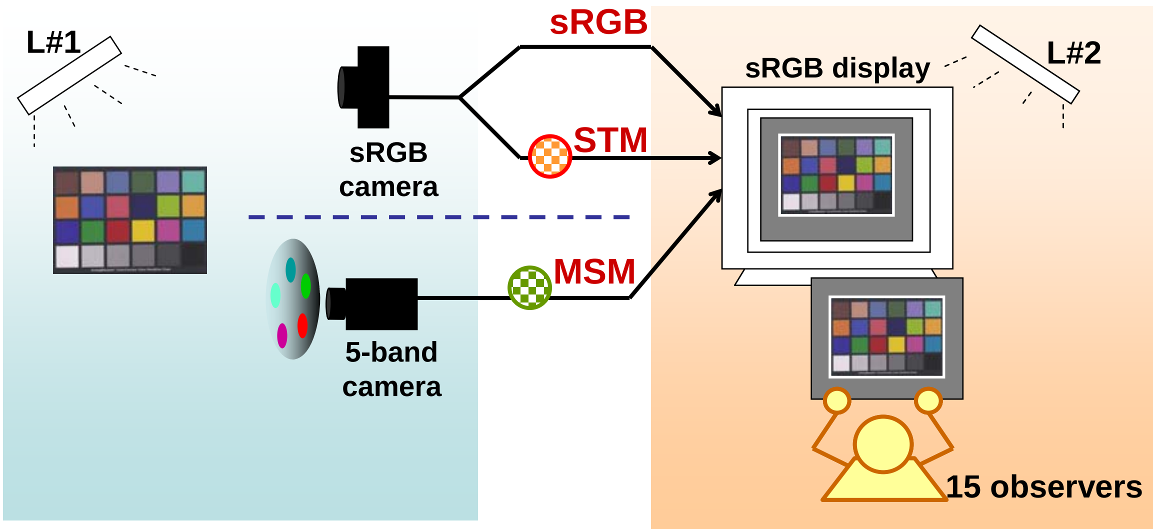

Figure 5 Procedure of observer rating experiment for comparison among sRGB method, MSM and STM.

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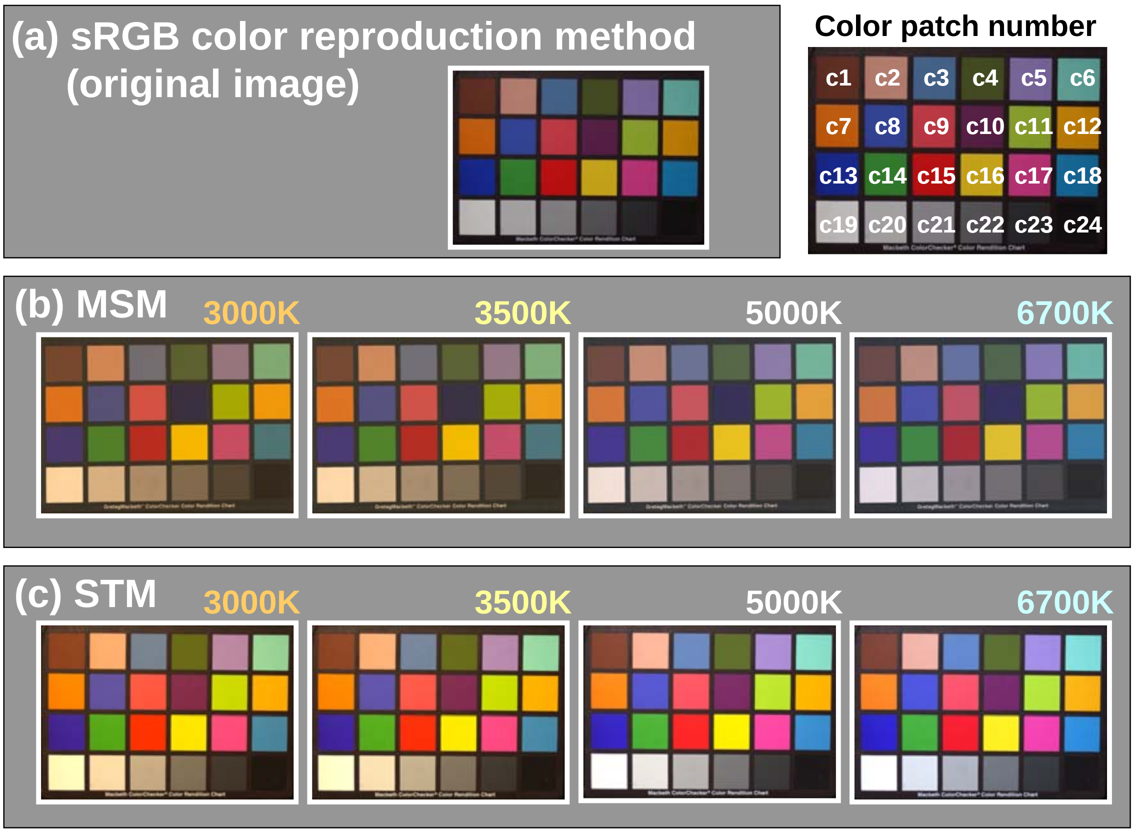

Figure 6 Reproduced images for 4 viewing conditions from sRGB color reproduction, MSM and STM.

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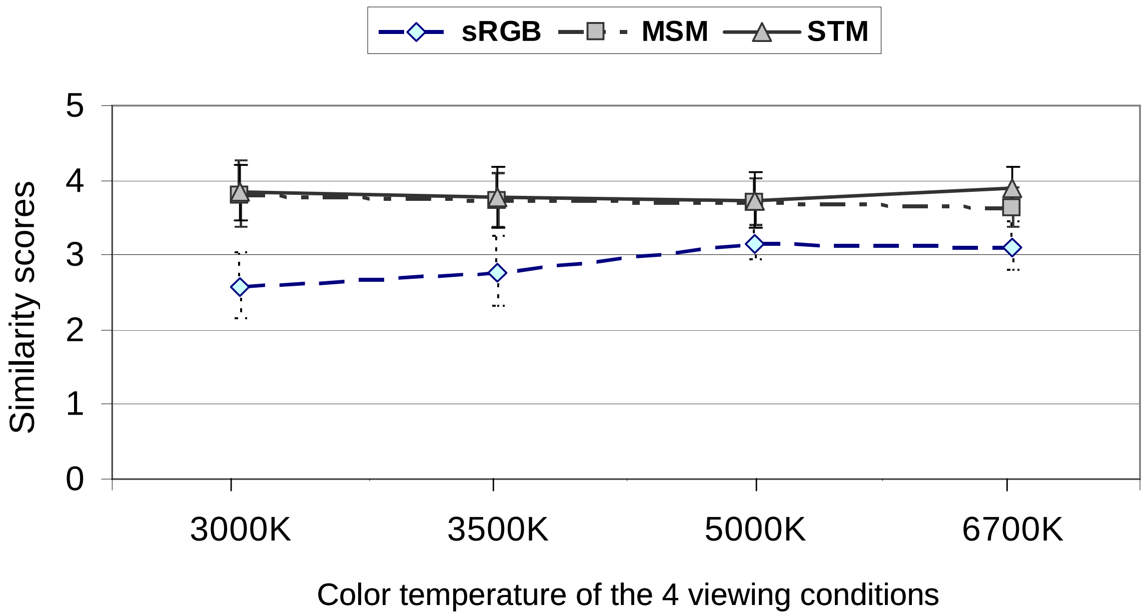

Figure 7 Average overall performances of three methods for 16 in-gamut colors viewed under the 4 light sources. Average calculated from the results of 15 observers.

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Kunlaya Cherdhirunkorn, Norimichi Tsumura, Toshiya Nakaguchi and Yoichi Miyake

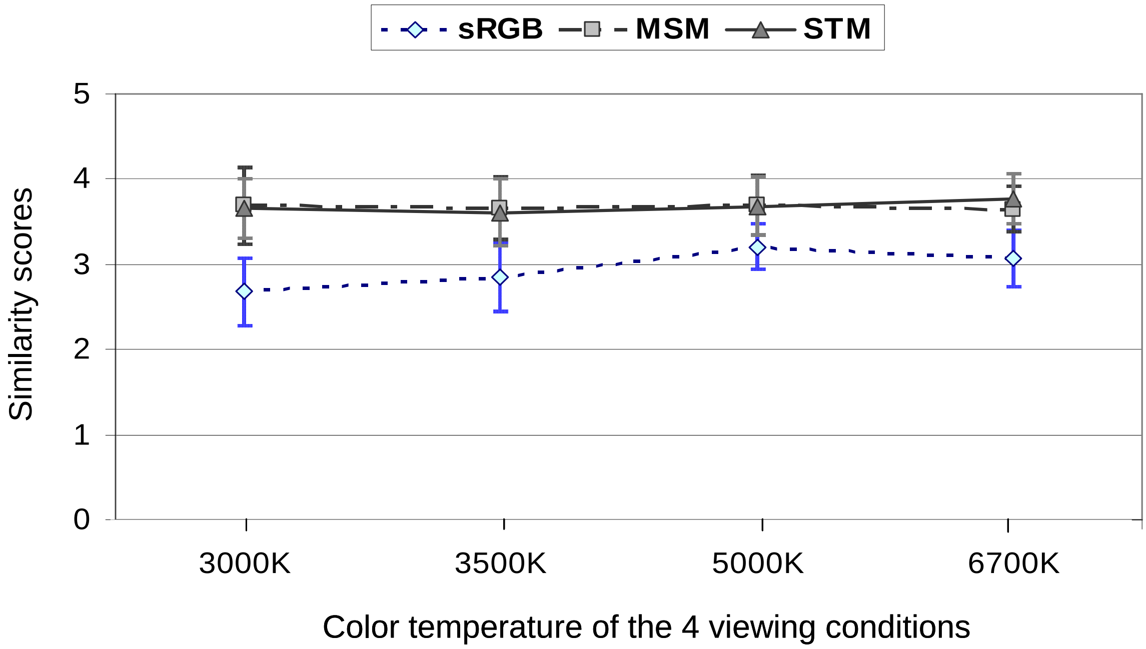

Figure 8 Average overall performances of three methods for all colors of Gretag Macbeth Color Checker Chart viewed under the 4 light sources. Average calculated from the results of 15 observers.

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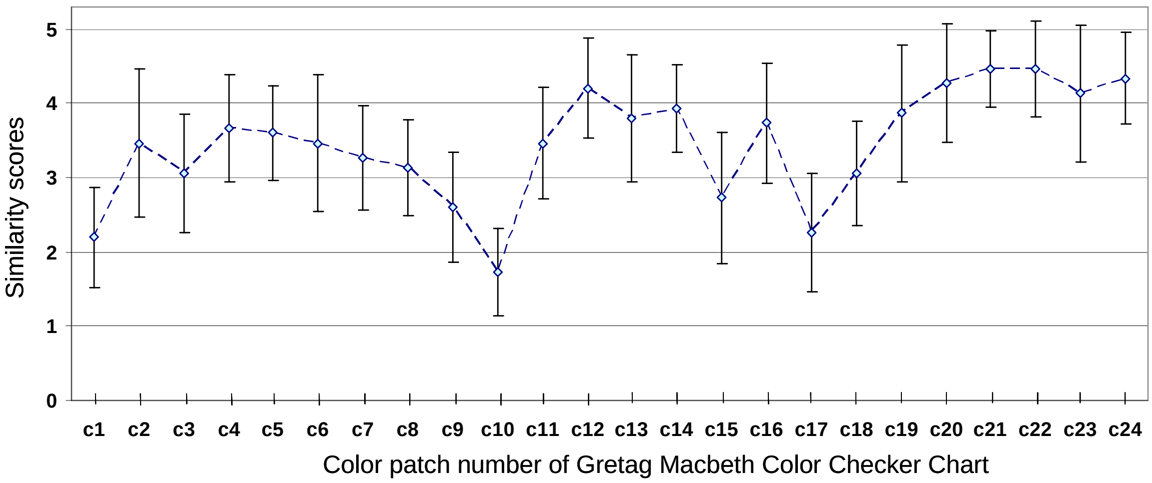

Figure 9 Performance of the sRGB method under the sRGB standard reference viewing conditions (D50, 64Lux).

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Table 1 Overall similarity scores

Score	Similarity level
5	Excellent
4	Good
3	Fair
2	Poor
1	Unsatisfactory

Table 2 The out-of-gamut colors (colors which have RGB tristimulus values located outside the sRGB gamut area) from the images reproduced by STM for 4 viewing conditions.

Out-of-gamut colors			
3000K	3500K	5000K	6700K
c2 (light skin)	c2 (light skin)		
c7 (orange)	c7 (orange)	c7 (orange)	
c9 (moderate red)	c9 (moderate red)	c9 (moderate red)	
c12 (orange yellow)	c12 (orange yellow)	c12 (orange yellow)	
c15 (red)	c15 (red)	c15 (red)	
c16 (yellow)	c16 (yellow)	c16 (yellow)	c16 (yellow)
c17 (magenta)	c17 (magenta)		
c19 (white, 0.05*)	c19 (white, 0.05*)	c19 (white, 0.05*)	c19 (white, 0.05*)

*optical density

Table 3 Average and standard deviation values of similarity scores of three methods for 16 in-gamut colors viewed under the 4 light sources. The average and standard deviation values calculated from the results of 15 observers.

	3000K		3500K		5000K		6700K	
	AV	STD	AV	STD	AV	STD	AV	STD
sRGB	2.58	0.44	2.77	0.47	3.15	0.23	3.11	0.32
MSM	3.8	0.45	3.72	0.36	3.7	0.32	3.64	0.26
STM	3.84	0.37	3.77	0.41	3.73	0.37	3.9	0.28

Table 4 Average and standard deviation values of similarity scores of three methods for all 24 colors of Gretag Macbeth Color Checker Chart viewed under the 4 light sources. Average and standard deviation values calculated from the results of 15 observers.

	3000K		3500K		5000K		6700K	
	AV	STD	AV	STD	AV	STD	AV	STD
sRGB	2.68	0.39	2.86	0.40	3.21	0.27	3.07	0.33
MSM	3.69	0.45	3.66	0.37	3.69	0.34	3.64	0.26
STM	3.65	0.35	3.61	0.39	3.68	0.34	3.77	0.30

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Table 5 Average and standard deviation values of similarity scores of sRGB method under the sRGB standard reference viewing conditions (D50, 64Lux).

Color patch	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12
AV	2.20	3.47	3.07	3.67	3.60	3.47	3.27	3.13	2.60	1.73	3.47	4.20
STD	0.68	0.99	0.8	0.72	0.63	0.92	0.7	0.64	0.74	0.59	0.74	0.68

Color patch	c13	c14	c15	c16	c17	c18	c19	c20	c21	c22	c23	c24
AV	3.80	3.93	2.73	3.73	2.27	3.07	3.87	4.27	4.47	4.47	4.13	4.33
STD	0.86	0.59	0.88	0.8	0.8	0.7	0.92	0.8	0.52	0.64	0.92	0.62

Overall average	STD
3.46	0.74