The Surround Color and Color Matching Functions

Changmeng Liu, Mark D. Fairchild; Munsell Color Science Laboratory, Rochester Institute of Technology; Rochester, NY

Abstract

Many research results indicated that the surround condition of image display could be a very important factor for image appearance. The most significant impact of the surround on image appearance is the change in perceived image contrast. The chromatic perception of the image will also depend on the color of surround. In this research, a psychophysical experiment was carried out to investigate surround color perception and its relationship with color matching functions and the impact of the macula. The first phase of the experiment was color matching across the center of the viewing field and the peripheral viewing field. The second phase of the experiment is verifying that the systematic color shift shown in the results of phase one was surround dependent but not device dependent. The result also showed that the 10° CMFs (color matching functions) are better than 2° CMFs to predict the tristimulus values of the display color when surround was considered. But neither 10° CMFs nor 2° CMFs could accurately predict surround color. A non-linear model was designed to predict the surround color perception. This model used a spectral filter, which was designed based on the density of Macula pigment. The results showed that this model could successfully predict surround color. The result of this research will help to better understand the impact of the surround on color and image appearance.

Introduction

When people attempt some color management tasks, the viewing conditions of the display will be a very critical variable; otherwise the color management might well be meaningless. Surround, as well as illuminant condition and some others, are very important components in the viewing condition.

Based on the definition used in color appearance models [1] for the simple color patches, the surround could be defined as the viewing field, which is 10° outside of the central stimuli. But for imaging applications, the surround is dependent on the application setup. In some cases where images are displayed on the display panels, the surround could be thought as the area outside the display panels. In some other cases, where the images are displayed as hard copy, the surround could be light booth or the peripheral area in the viewing room.

Previous research showed that the most significant impact of the surround on image appearance is changing the perceived image contrast. Based on the classical Bartleson's result [2] or Hunt's summary [3], the physical gamma ratio for average, dim and dark surround conditions would be 1:1.25:1.5 in order to perceive approximately same image contrast. Although some other research [4], [5] showed different gamma ratios for those three conditions, they all showed the same trends. Besides the perceived image contrast changing, the perceived chroma in image elements will also depend on the surround relative luminance. But this influence is a question that remains to be answered. [6]

Another application, that is mixed chromatic adaptation, is also closely related to surround conditions. The mission of CIE TC8-04 is *"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.color.org/tc8-04/) The surround condition can be treated as ambient light conditions if there are no other light sources in the viewing setup. Some researchers [7], [8], [9], investigated the color appearance influenced by ambient lighting conditions. Their results indicated that the ambient light caused subtle color shifting (10%~20%). These results were based on the achromatic color matching method and fixed state of chromatic adaptation. While, Katoh's result [10] indicated more adaptation shift (40%) if the adaptation is not fixed.

This research was directly motivated by the experiences from the previous surround research [5], in which the perceived image was measured under different surround conditions. In that experiment, the observers were forced to adapt to the surround condition every 30 seconds. During the adaptation time, the image display panel was colorimetrically set to the same color as the surround color, and the observers could freely look around the surround or display. But some observers complained that colors on the display panel and surround were not matched especially for those colors close to the neutral color.

If the surround color and central display color were colorimetrically set to same color or same CIE 1931 tristimulus values, the observer should perceive the same color across central display and surround. In other words, the ambient light is metameric to the central display panel. We can easily draw the conclusion that it should be no different in fixed state of adaptation or unfixed state of adaptation. So why did those observers complained about mismatching across the central display panel color and surround color?

There were two possible reasons to explain this shift. One possible reason is that the device models for LCD display and LED surround were not accurate. The other possible reason is that they were perceived as different colors by observer even if tristimulus values were the same. Let's assume our device model is accurate enough, although we knew that it is impossible to make zero color error across these two different devices. When we go back to check the workflow, it was easily confirmed that the physical spectral distribution curves of the surround and central display panel are not the same, they are at best metameric matches. It was also found that the color matching functions were not the same in this scenario either, an issue of observer metamerism.

The surround color was made up by diffused LED light, while the central display color came from an LCD display. They have significantly different spectral power distributions. They should be the same color when the tristimulus values were same to the degree the CIE color matching functions represent our observers. And we used the same color matching function applying on the two spectral curves to get the tristimulus values. The 1931 standard observer, also called the 2° color matching functions, was used in that research. But the viewing field is much larger than 2° viewing angle when we compare surround and central display panel. In this scenario, the color matching happened across the central retina and the peripheral retina. There was one big difference between those two parts of retina, which is the macular pigment.

The macular pigment protects the fovea, located roughly in the center of the retina, temporal to the optic nerve. It is a small (the diameter is about 1.5 mm) and highly sensitive part of the retina responsible for detailed central vision. 1931 2° color matching function already included the impact of macula. But peripheral retinal vision does not have the impact of macula. This could be the potential reason for explaining the perceptual color shift across surround and central display panel.

The hypothesis examined in this research was that the surround color was actually different from the central display even if the tristimulus values measured by colorimeter are same. If this is the case, different color matching functions will have different impact of measuring the surround color and central color. And a non-linear transformation of color matching functions using a filter based on the macula density could help to model the surround color perception. The experiment details below were designed to evaluate the hypothesis.

Experimental

The experiment was designed based on the hypothesis above that the perceived surround color is different from the central image or stimulus. In this case, it was not sufficient to just record the measured tristimulus value. Instead, the spectral distribution curves for each match were recorded in this experiment. A spectroradiometer (PhotoResearch PR650) was used in experimental measurement and device characterization for both surround LED and central LCD display panel. The experiments were run on an Apple Cinema HD LCD Display with the maximum luminance of 200 cd/m^2. This 23-inch LCD display has a 1920 by 1200 resolution. The display was carefully characterized using the colorimetric characterization model by Day [11]. The LCD display was set in a surround lab. More details about surround configuration can be found in the previous research [5], 12 uniformly distributed high power LED lights (Color Kinetics ColorBlast 12) were used to irradiate a white semicircle shaped diffusively reflective screen. Although the LED lights were uniformly distributed, the color on surround screen still contained some variation, for example the lower part of the screen was little bit brighter than the top part of screen. But the variation is continuous and not visually noticeable.

Experiment One

The first experiment was designed to test whether the perceptually same color on surround and central LCD display panel are colorimetrically the same color. Achromatic color matching method was used in this experiment. The reason is that the most obvious color inconsistency was located in the area where it is near the neutral axis. The observers in the previous research also complain more about the neutral color shift between surround and central display panel.

The observers were asked to sit in front of the LCD display. The viewing distance from LCD display was about 110cm. The viewing angle of LCD display was about 31° (width) by 16° (height). In order to avoid inter-instrumental error, the LCD display was characterized by the same spectroradiometer (PR650) as the one used in experimental surround measurement. We used the similar characterization model as the LCD model for the surround LED diffused screen. In this experiment, the accuracy of the surround screen model is not critical. The purpose of this model was just supplying a convenient way for the observers, so that they can easily change the color of surround screen. In the data collection phase, the spectral distribution of the surround screen was measured by PR650.

In this experiment, the color of central display panel uniformly filled the entire display screen. There were three testing achromatic colors with corresponding CIELAB lightness value equal to 100, 80 and 60. The CIELAB a*, b* values were set to zero. The white point was set to the native white of LCD display. For each testing LCD color, the observers were asked to change the color of surround screen by varying luminance Y and chromaticity coordinates u' and v' until it most closely matched to the central LCD color, and the both surround screen and central LCD display would be perceived as neutral color when the match was achieved. During the matching process, the observers were asked to focus on only one of four focus points, which were located near the center, top left, top middle, and top right corner of the LCD display. This process was similar to what happens when people are watching an interesting TV show, they would focus on the TV screen most of the time. It could also be described as fixed adaptation status. For each testing LCD color and focus point, the observers were asked to complete a matching procedure. After each match, the PR650 was used to measure the spectral distribution curve of the surround screen.

A total of 12 observers participated in this experiment. Each observer completed 12 matches in 4 focus point positions and 3 LCD testing colors. The experimental results discussed below showed a systematically color shift across surround color and central LCD color if the 2° CMFs were used to calculate the tristimulus values.

Experiment Two

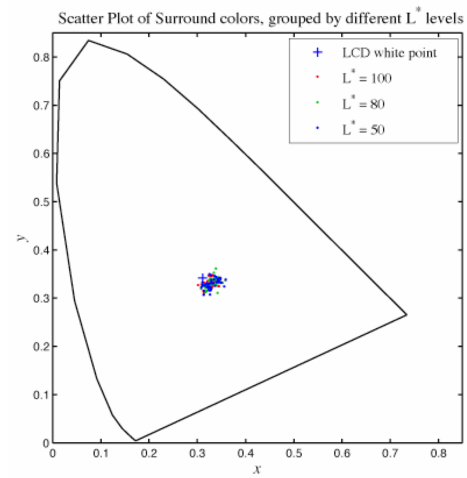
The second experiment was designed to verify that the systematically color shift result in experiment one was only dependent on the viewing angle but not because of the computation error.

In this experiment, a black box with two 2° square holes was constructed to block entire viewing field in the LCD display and surround screen. The observers could only see two color patches through two square holes. One stimulus was the color from the LCD display and the other one was the color from the surround screen. The observers were asked to match the colors of two stimuli by changing surround side color. During this experiment, the observers can freely change their focus point from one stimulus to the other one. After matching two colors, the spectral distribution curves were recorded by a spectral photometer. Due to a malfunction in the PR650 requiring that it be return to the manufacture, a Photo Research PR704, another spectroradiometer, was used in experiment two.

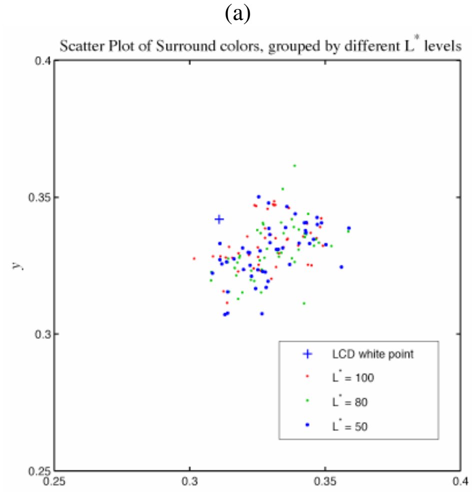
A total of 16 observers participated in Experiment Two. Each observer completed 3 matches across LCD display color and surround screen color through two 2° viewing windows. The experimental results discussed below were systematically different across surround color and central LCD color from the result from Experiment One for both 2° CMFs and 10° CMFs were used to calculate the tristimulus values.

Results and Discussion

Experimental One: Result using 2° CMFs



(a)



(b)

Figure 1. Scatter plot of LCD white point and its visually equivalent surround colors. (a) Each point represent one matching surround color from experiment one, data are grouped in corresponding LCD lightness levels, and the blue cross represent the white point of LCD display. (b) The zoom in plot of sub-figure (a), it shows the same information as (a) but with more details.

For the first experiment, the result is shown in Figure 1. Figure 1(a) and (b) show the same information, except Figure 1(b) shows more details because it was the zoom in version of Figure 1(a). In Figure 1, every point represents a matching surround color in chromaticity diagram from all observers' data calculated using 2° CMFs. The blue cross in Figure 1 represents the LCD white point. Because the chromaticity diagram cannot show the luminance variance, all three LCD testing colors fall in the same position as LCD white point in Figure 1.

The result in Figure 1 showed very clear systematic color shift between LCD white point and its visually equivalent surround colors. It was shown that all visually equivalent surround colors fall on the right bottom side of the LCD white point in the chromaticity diagram. This result indicated that surround color is not the "same" color as the central color if we used the traditional colorimetry to describe the color. This result indicates that the 2° CMFs were not a good choice for calculating the tristimulus values of the surround color. And obviously, the surround cannot be simply covered by 2° viewing field.

Experiment One: 2° CMFs vs. 10° CMFs

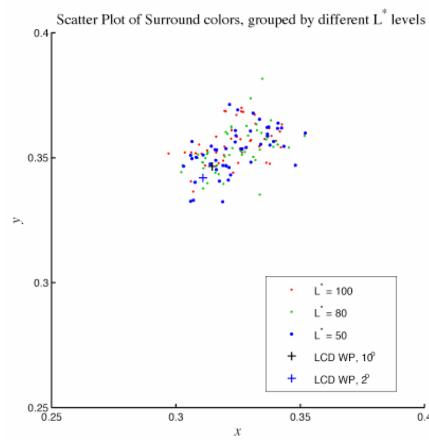


Figure 2. White point (WP) of LCD and its visually equivalent surround colors. The blue cross represent the LCD WP using 10° CMFs, black cross represent LCD WP using 2° CMFs. All dots in the plot represent the surround color calculated using 10° CMF; they were grouped by three corresponding testing LCD colors.

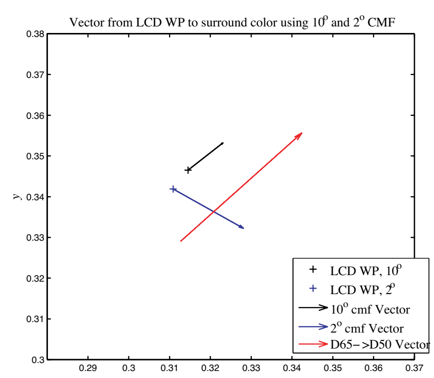
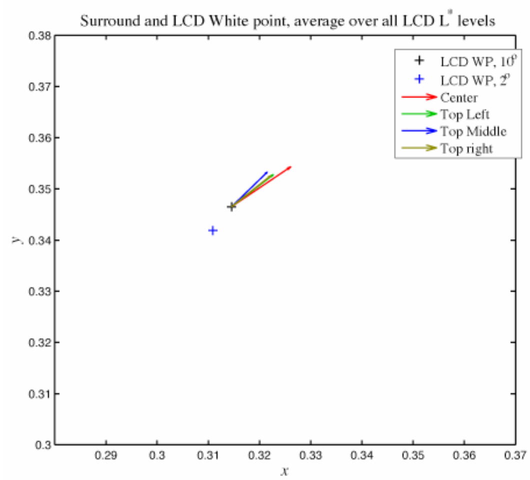
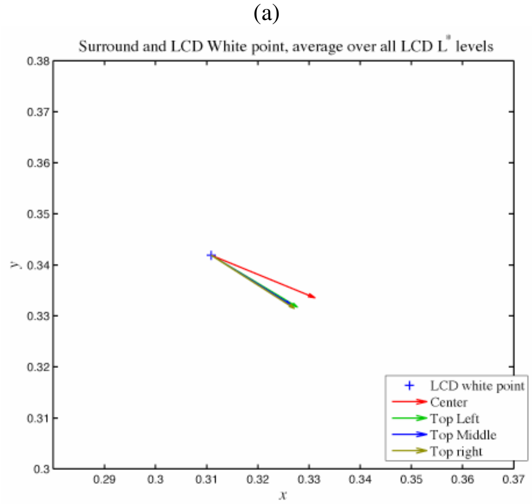


Figure 3. Comparing the 2° CMFs and 10° CMFs overall results. Two vectors start from LCD WP and terminated with the average of all surround colors. Blue vector was calculated using 2° CMFs black vector was calculated using 10° CMFs. Red arrow pointing from D65 to D50 white point as the reference color difference.

There was another choice of color matching function, which was the CIE 1964 10° color matching function. The result of using 10° CMFs is shown in Figure 2.



(a)



(b)

Figure 4. Comparison of the average result over different focus locations. (a) Using 10° CMFs. (b) Using 2° CMFs.

Figure 2 shows the experimental result using 10° CMFs. The blue cross represents the LCD white point using 2° CMFs; the black cross represents the 10° LCD white point. All dots in Figure 2 represent the visually equivalent surround color calculated using the 10° CMFs. If we carefully analyze the scenario in this experiment, the observers were asked to fix their focus on the LCD display, so the 2° CMFs might be more accurate to describe the central LCD color perception but not the surround color perception. By comparing the result from Figure 2 and Figure 1(a), it was shown that the 10° CMFs would be better to describe the surround color. But there still exists some systematic color shift between central LCD color and surround color.

Figure 3 shows the overall results by comparing 2° CMFs and 10° CMFs. In Figure 3, two vectors start from LCD WP and terminated with the average of all surround colors. Blue vector was calculated using 2° CMFs; black vector was calculated using 10° CMFs. In Figure 3, the red arrow was plotted from the D65 whitepoint to D50 whitepoint as the reference color difference. The result in Figure 3 indicates that the 10° CMFs are much better than the 2° CMFs to calculate the surround color. But as illustrated in Figure 3, the 10° CMFs still showed systematic error. This result agrees with the experimental scenario, because 10° viewing angle covered more surround area than 2° viewing angle. So it would not be surprising to see the 10° CMFs result was better than 2° CMFs result.

Experiment One: Different Focus Positions

In this experiment, there were four different positions upon which the observers were asked to focus. They were located at center of the LCD display, and positions close to top left corner, top middle, and top right corner. Around two corner positions, there were more surround area fall in the center-viewing field than other focus positions. Around the center focus position, there was no surround color fall in the center-viewing field.

Figure 4 shows the average result over different focus points. Figure 4(a) shows the result from 10° CMFs case, while Figure 4(b) shows the result from 2° CMFs case. The result in Figure 4 shows that the mismatching between the surround color and LCD white point was most significant when observers were asked to focus on the center of LCD display. This observation can be found in both 2° and 10° CMFs cases. It also shows that the color shift was still very significant even if the focus point was located near the corner of LCD display.

Experiment Two: Verification Experiment

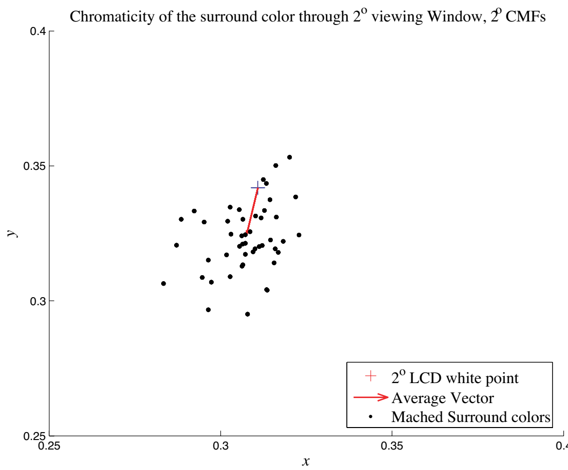
For the second experiment, the results are shown in Figure 5. Figure 5 (a) shows the result that plot the LCD white point with its visually equivalent surround colors through two 2° viewing windows; all data shown in Figure 5 (a) were calculated by using 2° CMFs. Figure 5 (b) shows the similar result to Figure 5 (a); but all data shown in Figure 5 (b) were calculated by using 10° CMFs.

Table 1. Chromaticity Coordinates of LCD white point and surround colors in Exp 1 and Exp 2

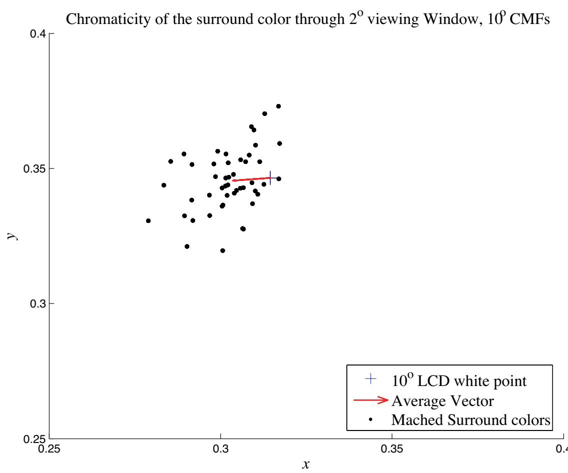
Chromaticity Coordinates	x	y
LCD white point, (2° CMFs)	0.311	0.342
Exp 1, Avg. Surround, (2° CMFs)	0.330	0.331
Exp 2, Avg. Surround, (2° CMFs)	0.307	0.323
LCD white point, (10° CMFs)	0.315	0.347
Exp 1, Avg. Surround, (10° CMFs)	0.324	0.354
Exp 2, Avg. Surround, (10° CMFs)	0.302	0.345

The difference between Experiment Two and Experiment One is the viewing angle was narrowed down from 180° whole viewing angle to 2° limited viewing angle. By comparing the results in Figure 5 (a) and Figure 1 (b) for 2° CMFs case or comparing the results in Figbure 5 (b) and Figure 2 for 10° CMFs case, it is found that the data distribution of the matched surround colors in the chromaticity diagram are systematically different between these two viewing condition (180° viewing angle and 2° viewing angle). Table 1 shows the chromaticity coordinates of the reference LCD white point calculated using 2° CMFs and 10° CMFs and their average visually equivalent surround colors in Experiment One and Experiment Two.

The average surround matching color in Experiment Two do not exactly match to the reference LCD white point color in chromaticity coordinates. The errors in Experiment Two could be generated from the observer metamerism that means the observer in our experiment are not the perfect 1931 2 degree standard observer. The other possible reason is the instrumental uncertainty because of using two different spectroradiometer. The instrumental error should not be significant. And the last possible reason for the error could be the configuration of the experimental setup was different from the experiment in getting 1931 standard CMFs. Considering these reasons for the measurement errors, the 2° CMFs is acceptable for using in this verification experiment.



(a)



(b)

Figure 5. White point (WP) of LCD and its visually equivalent surround colors through two 2° viewing windows. The red arrow point to the average of the all points form the LCD WP. In Figure 5(a), the black dot represent the surround color calculated using 2° CMFs, the red cross represent LCD WP using 2° CMFs. In Figure 5(b), the black dot represent the surround color calculated using 10° CMFs, the blue cross represent LCD WP using 10° CMFs.

The average matching color in Experiment Two are 22% closer to the reference LCD white point color in chromaticity diagram than the average matching color in Experiment One for 2° CMFs. And the directions of the vectors are different by comparing red arrow in Figure 5 (a) and the blue arrow in Figure 3. For 10° CMFs case, the length of red arrow in Figure 5 (b) is almost the same as the black arrow in Figure 3, but the directions of the arrows are totally different. This result verifies and confirms that the peripheral vision is different from the central vision.

Modeling the Surround Color Prediction

As mentioned in the previous section, the difference between central vision and peripheral vision is that the macula is only present on the central vision and it is well known that the macular density varies significantly from person to person (or even between left and right eyes). In order to model the surround color perception, we need to adjust the impact of the macula from the 2° or 10° standard CMFs. In this research, we proposed a non-linear model to predict the surround color based on the density curve of macula filter. It is non-linear in the sense that the modified CMFs (and therefore the tristimulus values) are not a linear transform of the original CIE CMFs.

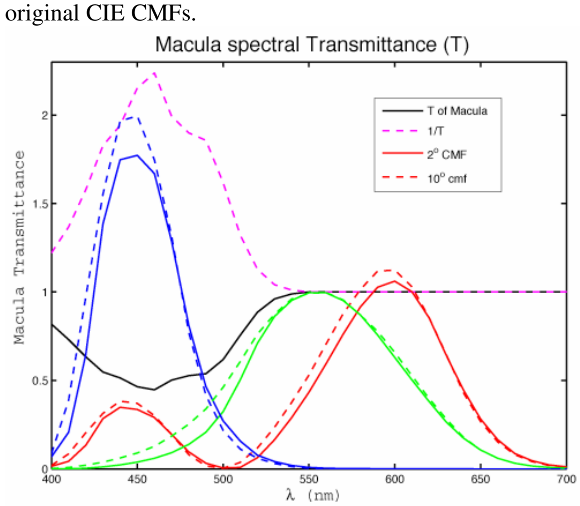


Figure 6. Transmittance of macula. Plotted with 2° and 10° CMF.

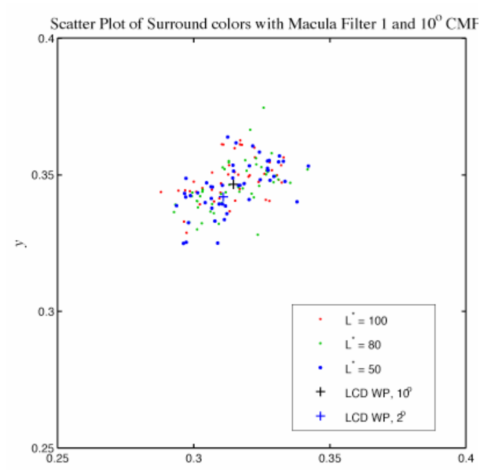


Figure 7. Surround color after using this non-linear model.

The first step of this model is transferring the macular density data to transmittance data using equation (1).

$$T_\lambda = 10^{-D_\lambda} \quad (1)$$

Where, T_λ is the transmittance curve of macula, D_λ is the density curve of the macula. [12] Figure 7 shows the transmittance curve of macula and compares it with 2° or 10° standard CMFs.

The second step is transferring the spectral distribution curve of the surround to tristimulus value using equation set (2)

$$\begin{aligned} X &= \int_\lambda \bar{x}.R_\lambda.F.d\lambda \\ Y &= \int_\lambda \bar{y}.R_\lambda.F.d\lambda \\ Z &= \int_\lambda \bar{z}.R_\lambda.F.d\lambda \\ F &= 1/((T_\lambda - 1).f + 1) \end{aligned} \quad (2)$$

Where, $\bar{x}, \bar{y}, \bar{z}$ are the CIE color matching functions. We suggest using 10° CMFs. R_λ is the reflectance spectral distribution of surround field. F is a function of the transmittance of the macula T_λ . f is an optimized rescale factor to rescale T_λ to represent variable macular adjustments between display and surround.

The F function was shown in Figure 6 as 1/T curve, where the f was equal to 1. Figure 6 shows that F function will boost the l and s cone response and have little impact on m cone. As a result, the color shows in chromaticity diagram will be move to blue direction if we used this F function. The optimum f value is 0.19. The objective of the optimization was the Euclidean distance between the tristimulus values of surround and LCD colors. After this model, the average of the experimental data was move to the position of LCD white point in the chromaticity diagram. Figure 7 shows the scatter plot after using this non-linear model to predict the surround color. Comparing the result between Figure 7 and Figure 2, it was shown that this model would greatly improve the accuracy for the surround color prediction.

The limitation of this model is that it needs the spectral data of the surround. Because it is a non-linear model, it cannot directly correct the surround color from tristimulus value measured by a colorimeter.

Conclusion

In this research, a psychophysical experiment was designed to investigate the surround color perception and its relationship with color matching function and macula. The results showed that the tristimulus values would be different even if the colors were visually same across the surround and central display panel. The results also showed that 10° CMFs would be better than 2° CMFs when dealing with surround colors. But neither 2° nor 10° CMFs would be accurate for calculate the tristimulus value of surround color, which fall in the peripheral vision field. The color shift was most significant when the observers were focused on the center of LCD display. A non-linear model was developed to predict the surround color based on the macular transmittance curve. The results show that this model can successfully predict the surround color.

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Author Biography

Changmeng Liu received his B.S. degree in EE Department from TianJin University (China) in 1996 and M.S. degree in Computer Science Department from the Rochester Institute of Technology in 2002. He is a Ph.D. candidate in the Munsell Color Science Laboratory at the Chester F. Carlson Center for Imaging Science at the Rochester Institute of Technology