Observer Accuracy and Variability in Metameric Color Matching Experiment

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ABSTRACT

The color matching experiments were conducted using ten pairs of RGB LED lightings. The results showed that when the peak wavelengths were different between the reference and the test, there was the systematic colors shift in CIELAB color space and the metameric pair having low accuracy shows large observer variabilities.

1 Introduction

The human eye perceives color through three types of photoreceptors: L, M, and S cones and each human eye have slightly different characteristics causing observer metamerism. Recently, with the advent of wide-color-gamut displays, observer metamerism has become a major issue for the display industry. The wide-color-gamut displays emit strong light in a specific wavelength range, causing a high degree of metamerism [1,2]. In this regard, there have been various studies on measuring the degree of metamerism [3,4]. These studies showed that CIE standard observers fail to predict the color matching data and the observer variability cannot be ignored [5,6]. Therefore, a new color matching function is needed which can well represent human vision better and also considers the individual differences. To achieve this goal, various color matching experimental data sets are required.

New metameric color matching data set is collected in this study using ten pairs of LED lightings having various RGB primaries to evaluate the change of observer variabilities by primary set changes.

2 Experiment

2.1 Experimental Setting

The experiment was conducted using two spectrum-tunable LED lighting booths in a darkroom. The opened areas of lighting booths were covered with the diffuser and then with black papers except for a circle with a diameter of 8.8 cm in the center. Therefore, in the darkroom, two circles were shown to the participant as shown in Fig. 1 and the distance between the centers of the two circles was 8.8 cm. The left circle was the reference stimulus, and the right was for the test stimulus.

Each participant was positioned at a distance of about 80 cm from the lighting booth so that each circle's viewing angle was about 10° and the total field of view corresponds to 10° X 30° as described in Fig. 1 (b).

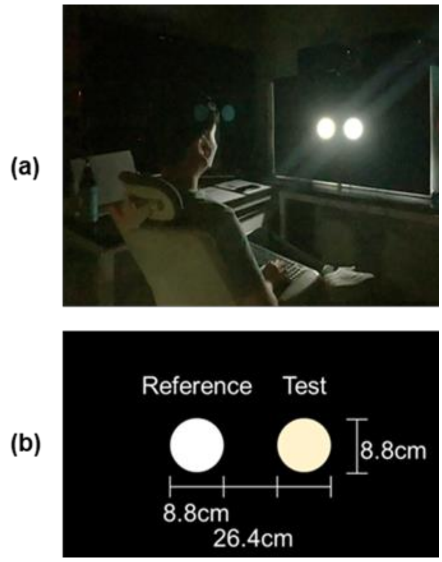

Fig. 1 Experimental Setting
((a) Experimental environment, (b) Test scene)

2.2 Selection of Reference and Test Stimuli and Color Control Algorithm

Two LED lighting booths having 15 channels were used to generate the reference and test stimuli. The reference stimulus was set to simulate D65 illuminant as shown in Fig. 2. CIE 1964 tristimulus values, $X_{10}Y_{10}Z_{10}$, of the reference white were [32.56, 34.84, 36.60].

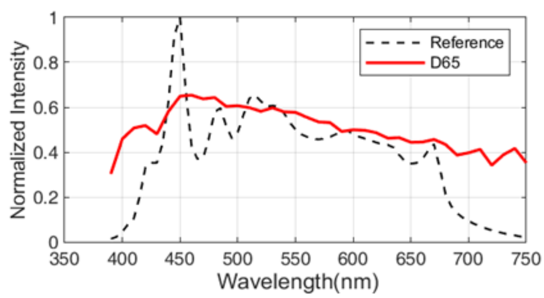

Fig. 2. Spectrum of the reference stimulus

As test stimuli, ten RGB primary combinations were selected as shown in Fig. 3 simulating the various imaginary display color primaries but not reflecting the actual display characteristics.

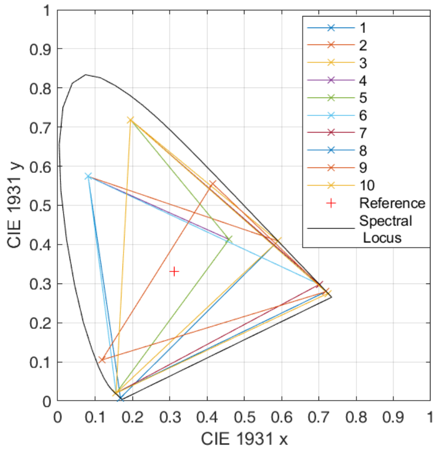

Fig. 3 Reference & 10 Test primary sets

The LED color control program was developed to manipulate the test stimulus using the keyboard in CIELAB color space. For each RGB primary color set, the tone curve of each LED channel was measured to formulate the GOG model, which was used to convert LED RGB channel intensity to CIELAB and vice versa.

2.3 Experimental Method

In the experiment, the participant directly manipulates the test color using the keyboard to have the same color appearance with that of the reference. Prior to the experiment, the participants learn about CIE L*a*b space and how to change the L*a*b* of the test color using a keyboard.

Before the metameric color matching, to evaluate the observer performances on color matching task, three colors matchings, T1, T2, T3, were conducted using the same primary sets both for reference and test colors. T1 looked similar to 6500K light while T2 and T3 showed slightly green and magenta tint respectively. Fig. 4 compares the relative spectrums of T1,2 and 3.

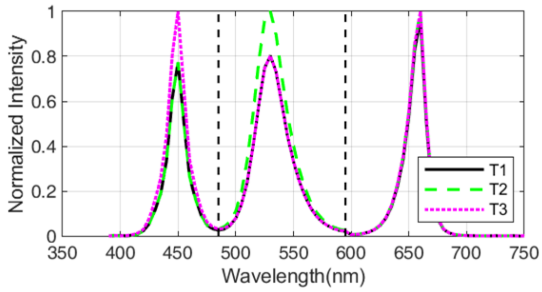

Fig. 4 Reference colors for color matching accuracy test

After the observer performance test, ten metameric color matchings were conducted in order. In total, 25 people who have normal color vision participated the experiment. The average age is 25.7 years. (15 Females, 10 Males). For the performance test, each participant matched each pair once and the metameric color matching was repeated three times for each RGB primary set resulting in 75 color matching data points per pair.

2.4 Data Analysis Method

After each color matching, the spectral data of reference and matched colors were measured with a spectroradiometer (Konica Minolta, CS2000). Then CIE 1964 tristimulus values were calculated both for the reference and matched test colors.

The color matching results were analyzed in terms of 'color matching accuracy' and 'observer variability'. The color matching accuracy is to measure the performance of CIE 1964 color matching function and the observer variability is to measure the individual differences in the color matching data set.

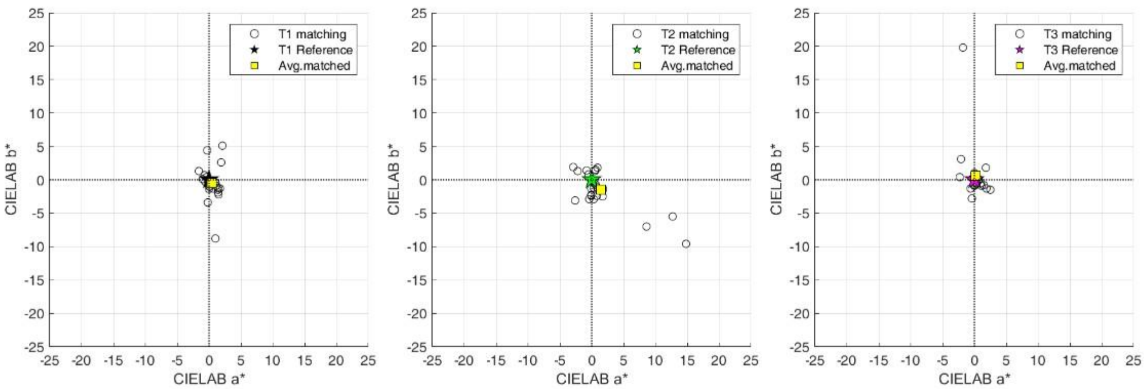

Fig. 5 Color matching accuracy test results

The 'color matching accuracy' was measured using the color difference between the reference color and the individual matched colors and 'observer variability' was quantified as the color difference between each color matching color and the average of 75 data points.

To evaluate the color difference, CIELAB color values were calculated using the reference color as the reference white, and then ΔE^*_{ab} between two colors was calculated.

3 Results

3.1 Observer Performance: Color Matching Accuracy

When the exactly same RGB primaries were used both for the reference and the test, ideally, the exactly same colors had to be generated as the matched color but because of the human errors, the color mismatch could happen.

Fig. 5 shows the color matching results for T1, T2, and T3 stimuli. The horizontal axis represents CIELAB a* and the vertical axis represents CIEALB b*.

In terms of color matching accuracy, the average ΔE^*_{ab} were 3.66±2.18, 5.93±4.84, and 4.60±4.27 for T1, T2, and T3 respectively. Most of the participants showed high accuracies but there were 1, 2, and 2 observers who showed low accuracy having ΔE^*_{ab} larger than 8.02, 15.62, and 13.13 (Average + 2σ). Excluding the outliers, the average accuracy become 3.30±1.82, 4.54±2.70, and 3.63±2.07 for T1, T2, and T3 respectively. However, there was no participant who showed poor performance for all three test colors indicating the importance of training and repetition for color matching experiment.

In the case of the observer variability, ΔE^*_{ab} of T1, T2, and T3 were 3.37±2.27, 5.11±4.30, and 4.66±4.15 for all 25 observers and 2.97±2.10, 3.94±3.02 and 3.69±1.99 when the outliers were excluded.

3.2 Metameric Color Matching Results

Table 1 summarizes the metameric color matching results in terms of 'color matching accuracy' and 'observer variability'. The total average ΔE^*_{ab} for color matching accuracy was 8.27±4.42. The total average ΔE^*_{ab} for observer variability was 5.27±2.89.

Table 1. Color Matching Results

Primary No.	Accuracy(ΔE^*_{ab})	Variability(ΔE^*_{ab})
1	12.98	6.21
2	4.16	3.97
3	8.90	4.80
4	4.45	4.05
5	8.95	5.27
6	10.70	6.67
7	6.19	4.32
8	7.62	5.02
9	11.68	6.84
10	7.03	5.54
Average	8.27	5.27

Results indicate that each metameric pair shows very different characteristics and the metameric pairs having high accuracy also show small observer variabilities.

The experimental data were further analyzed comparing the spectral characteristics with the color matching results.

Fig. 6 (a) compares the results of No.2, 4, and 5 primary sets. Primary set No.2 and No.4 show very good color matching accuracies and low observer variabilities and it is notable that No. 2 and 4 primary colors peak wavelengths are the same with those of the reference.

No.5 primary set has the same blue and green primaries but 20 nm difference for green primary spectrum compared to those of No.4. Such wavelength difference caused the color shift in the a* direction between the average color matching data points and the reference.

Fig. 6 (b) compares No.2 with No.1, 3 and 6. Compared to No.2, blue primary of No.1 was shifted from 445nm to 420nm, resulting in color shift in b* direction. In the case of No.3 and 6, the green primary was changed from 505nm to 525nm and red primary was changed from 595nm to 635nm respectively compared to No.2 and there were color shifts in a* direction.

Fig. 6 (c) compares the matching results between No.7, 8, and 10. Those three primary sets share the same green and blue primaries but different red primaries. All of them show the same degree of color shifts in a* direction indicating that the peak wavelength differences in red primaries didn't affect the color matching result significantly.

4 Conclusions

New set of metameric color matching data were collected using two spectrum tunable-LED lighting booths. 10-degree colors generated from the D65 simulator and ten different RGB primary color sets were matched by 25 participants in a darkroom. After color matching experiment, both reference and the matched colors were measured and presented in CIELAB color space for further analysis.

When the participants were asked to match the colors having the same primaries, the average color matching accuracy was 4.73±3.99 in terms of CIELAB color difference between the reference and the matched color, and the average observer variability was 4.38±3.71 in terms of CIELAB color difference between the average matched color and the individual matched color.

The metameric color matching results were strongly affected by the spectral characteristics of the test colors. When the peak wavelengths were the same between the reference and the test spectrums, the accuracy was high and variabilities was small. However, as the peak wavelengths were different from the reference, there was the systematic colors shift between the reference and the matched in CIELAB color space. Also, it was found that the metameric pair having high accuracy shows small observer variabilities.

In conclusion, this study confirms the previous studies that CIE 1964 color matching functions fail to predict the color matching results and the individual differences needs to be considered requiring further intensive color matching studies for wide color gamut displays.

Acknowledgement

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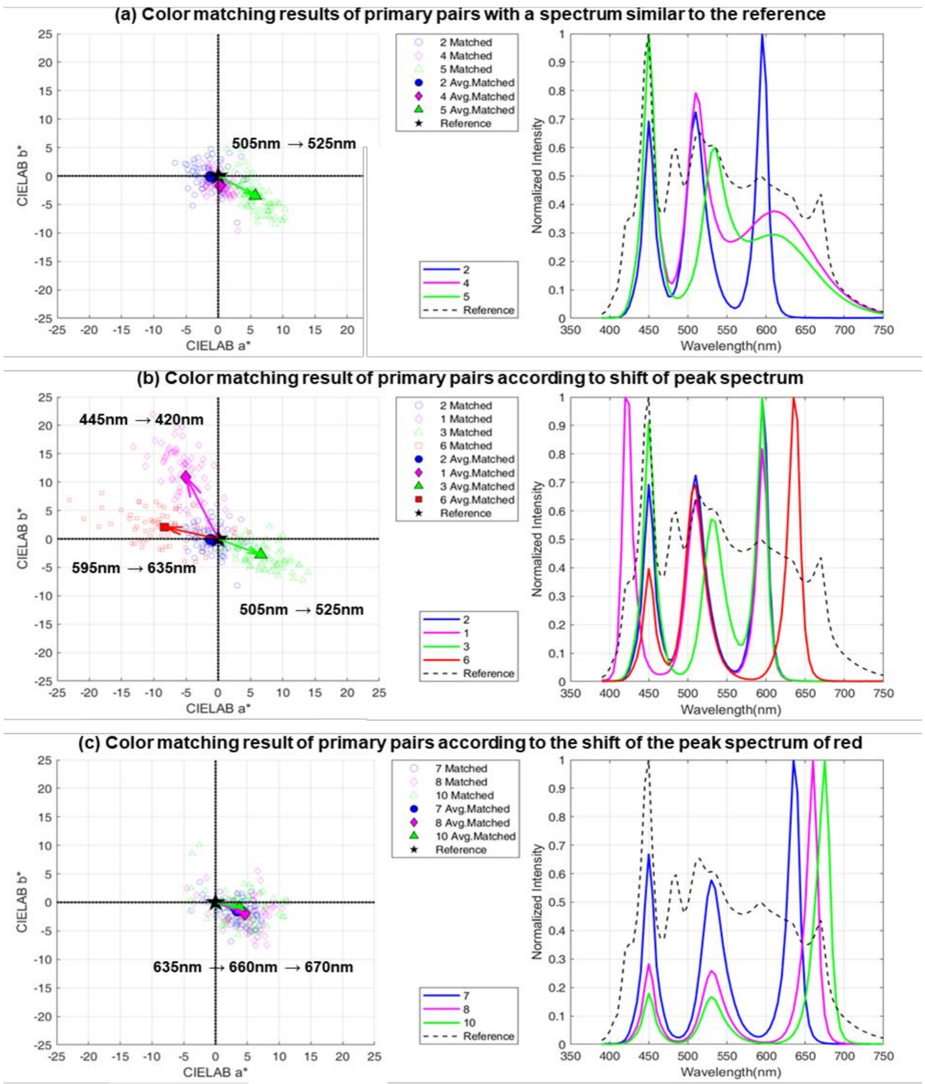

Fig. 6 Metameric color matching results