Color-Matching Function Affecting Color Reproduction in Displays

Ming Ronnier Luo* *** , Siyuan Song* ***, Andrew Stockman* **

*College of Optical Science and Engineering, Zhejiang University, Hangzhou, Zhejiang, China
**CL Institute of Ophthalmology, University College London, London, UK
***State Key Laboratory of Extreme Photonics and Instrumentation, Zhejiang University, Hangzhou, China

Abstract

The paper first summarizes the problem in using CIE 1931 2o color matching function (CMF) for display colorimetry. A visual trichromator will be introduced to obtain 100 Chinese individual CMFs. Its performance was compared with the other CIE CMFs using two independent cross-media color matching experiments. It shows the individual CMF agreed better than the other CMFs. Finally, the possible standards and applications on individual CMFs will be described.

Author Keywords

Color matching function, individual Color matching function, cross-media color matching

1. Introduction

Individual persons possess different color vision, which can be quantified by the color matching function (CMF).

For practical applications, CIE recommended four CMFs: 1931 2º [1-3]and 1964 10º [4], 2006 2º and 2006 10º [5, 6]. These are plotted in Figure 1.

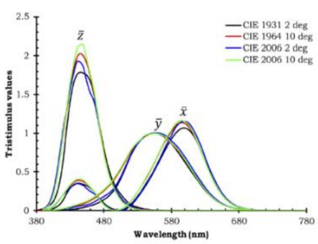


Figure 1. The 4 CIE CMFs

For display colorimetry, the matrix formula in equation 1 is used to calculate the tristimulus value.

$$X = C\ S\ R \qquad (1)$$

where X represents XYZ, a 3x1 matrix; C represents CMF, a 3 by 31 matrix, S represents the spectral power distribution (SPD) at the maximum intensity of the three channels, a 31 by 3 matrix, and R is RGB digital counts, a 3 by 1 matrix. Note 31 means the visible range from 400 to 700 nm with 10 nm interval.

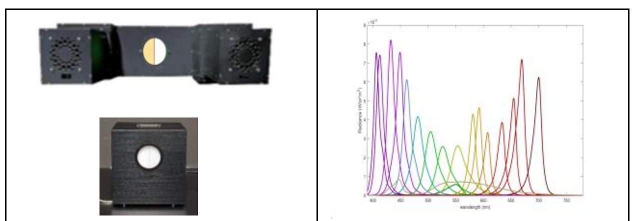
Conventionally, the CIE 1931 2º CMF has been adopted in the imaging industry and 1964 10º for the surface industry. The CIE 2006 2º and 10º CMFs were derived from the three photopic cone receptors, L, M, S for long-, middle- and short- cone sensitivity functions respectively [5-7].

When applying display colorimetry, same XYZ values of the two stimuli means a color match between them. More recently, it was found significant mismatch between two stimuli having the same XYZ values under CIE 1931 2º observer [8, 9]. This was caused by the significant shortage of energy for the range around 460 nm as shown in Fig. 1, which is the position of typical blue LED used for the lightings and displays.

In 2021, a large project, named LEDMax, was established between Zhejiang University, University College of London and Thouslite limited (China). The goals were to establish a visual trichromator to perform color matching, and to accumulate Individual CMF (ICMF) for 100 observers across a large age range. The goals were successfully achieved and the results were reported [10-12]. In this paper, two experiments were carried out to perform cross media color reproduction to compare ICMF with CIE CMFs. It is expected that this paper summarizes these developments.

2. LEDMax project

In the top of Figure 2a shows the apparatus, also named LEDMax, visual trichromator used in the experiment. It includes two identical units on each side, each including 18 LEDs. Figure 2b plots their SPDs from 400-700 nm. The triplet LED lights are evenly mixed and projected into the middle bipartite field. Observers performed 11 color matches to the left side reference white (7500K) by adjusting the RGB or L*a*b* controls on the right side. For each color match, the lights were a combination of the triplet LEDs in the red, green and blue regions respectively (see Figure 1b). The bottom of Figure 2a is a condensed the latest version of LEDMax system.



(a) Apparatus | (b) SPD of the 18 LEDs

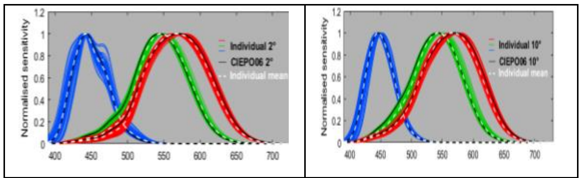
Figure 2 The LEDMax system.

The matched results were then measured in terms of SPD and further analyzed to report the 7 physiological parameters for each observer (optical densities of macular, lens pigments, L-, M- and S- pigments, and spectral shifts of the L- and M-cone pigment). From those, the LMS CMFs can be derived based on the CIEPO06 model derived by Stockman and Rider [13]. These can be further transformed to $\bar{x}, \bar{y}, \bar{z}$ CMF. Detailed description of the LEDMax and its performance can be found in Shi et al [10].

Finally, the 100 Chinese's CMFs, including 47 and 53 male and

ISSN 0097-996X/25/5602-0998-$1.00 © 2025

female respectively, were accumulated. They were divided into 7 age groups with mean of 10, 25, 35, 45, 55, 65 and 75 years old. The 100 observers' 2º and 10º LMS CMFs are plotted in Figure 2. The detailed results can be found in Shi et al. [12].



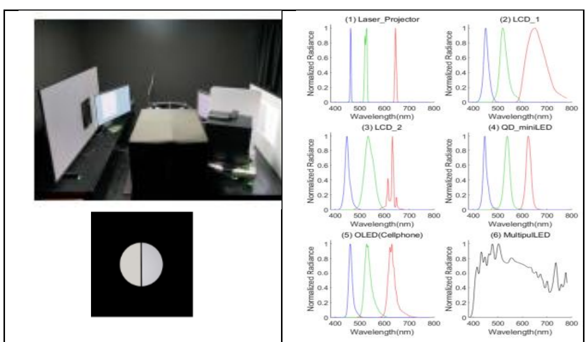
(a) 2o | (b) 10o

Figure 2 CMFs from 100 Chinese observers

Cross-displays color matching experiment

Ten observers took part and they first performed 10º color matching task using LEDMax system. Note the experimental design was different as described in Section 2. Only 5 pairs of white stimuli from the triple LEDs were used here rather than to match same white using 11 triplets. In other words, the two stimuli in each viewing field are different. Only the 10º degree field was used in this experiment. The matching data were used to generate each observer's ICMFs.

In the display experiment, 6 displays were specially selected to represent the state of the art display technology, including a Laser, 2 LCDs, an OLED, a QD-miniLED and an D65 illuminant simulator. Figure 3a shows the color matching set up. This allows for the selection of a pair of displays, and their light can be guided via a tunnel to display stimuli in each side of biparty viewing field. Figure 3b shows the SPD for each display. It can be seen that there are large differences in peak wavelengths and half band width. Ten observers were asked to adjust one display white to match the other display, located in both sides using L*a*b* controls. In summary, 11 pairs of display white were matched for each observer. Each observer repeated twice. Overall, 220 matches were made, i.e. 11 pairs x 2 repeats x10 obs. The results were used to test all CMF's performance in the next sections.



(a) Set up for the display experiment | (b) The SPD for the displays

Figure 2 The set up for the cross-displays experiment

3. LEDSimulator experiment

In this experiment, the LEDSimulator® from Thouslite was used as shown in Figure 4a. It was designed to produce appearance from virtual samples having different colors on different textures. Five observers looked at a surface sample under the D65 illuminant simulator in a light cabinet. A window is located in the back wall of the cabinet (see Figure 4b). It is filled by a uniform color by projecting 3-LED light on to a white surface. Only the 10º field of view was used. Overall, 225 matchings were made, i.e. 5 observers x 3 repeats x 15 colors.

Same 5 observers also conduct color matchings using LEDMax system for both 2º and 10º fields. In total, 550 colors were matched, i.e. 5 observers x 5 repeats x 11 matches x 2 fields. The results were used to test all CMF's performance in the next sections.

(a) Set up for the cross-media experiment | (b) The color matching fields

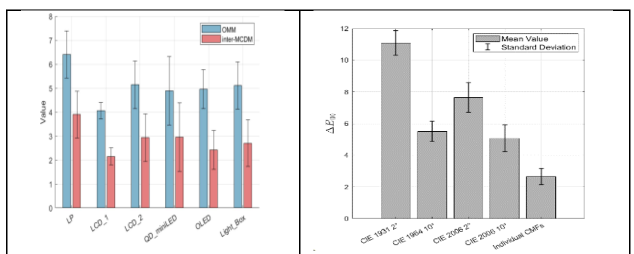
Figure 4 The set up for the LEDSimulator experiment

4. Results

Cross-display Experiment

The observer variations are first reported. The results showed that the inter- and intra- observer variations in CIEDE2000 [14] (ΔE_{oo}) units were 2.82 and 1.14 respectively using displays, and 4.06 and 1.25 units respectively using LEDMax.

Figure 4 plots the results of OMM-MCDM and OMM. In the figure, where OMM-OCDM is similar to inter-observer variation, and OMM is the observer metamerism index [15], representing color accuracy. As expected, the OMM values were larger than OMM_OCDM by about half. The average ΔE_{oo} values showed 5.2 and 2.9 units respectively. It can also be seen that the Laser display performed the worst, having the poorest accuracy, due to its sharp peak wavelength and narrow half band width (see Figure 3b). The other displays gave similar performance.



(a) Inter-MCDM and OMM | (b) The CMFs' performance

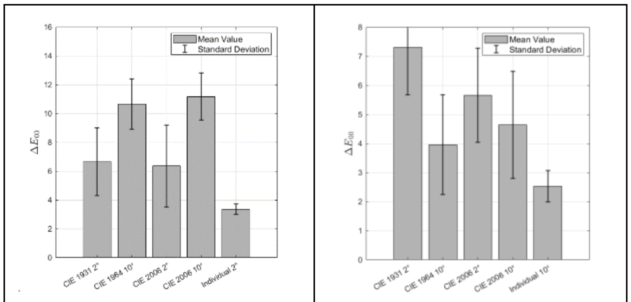
Figure 4. The results from the Cross-displays experiment.

When comparing different CMFs' performance, it can be seen that both 2º CMFs performed worse than both 10º CMFs. This is expected because 10º field was used in the present experiment. Note 1931 2º CMF was still performed the worst. However, the ICMF significantly outperformed the others. This strongly indicates the color performance of the displays can be greatly improved by adopting observer's own CMF.

LEDSimulator Experiment

In the experiment using LEDMAx by the 5 observers, the inter-and intra- observer variations were again first compared. It was found for the 10º results, the mean inter- and intra-observer variations were 2.04 and 1.06 ΔE_{oo} units, respectively, and 3.55 and 1.54 units, respectively, for the 2º inter-observer variations.

When comparing the CMFs' performance, it can be seen that for 2º observer LEDMax results, both 2º CMFs outperformed both 10º CMFs, similar to the Cross-displays experiment. The trend is also shown in 10º experiment. Overall, 1931 2º CMF predicted the least accurate to the 10º experimental results.



(a) 2º (b) 10º

Figure 5 The CMFs' performance for the LEDMax experiment

In the experiment using LEDSimulator, the inter- and intra-observer variations were again first compared. It was found the mean inter- and intra-observer variations were 2.12 and 0.62, ΔE_{oo} units, respectively

Comparing the CMFs' performance to predict the visual results, it can be found that ICMF clearly gave the most accurate prediction, followed by the others, and 1931 2º CMF performed the worst.

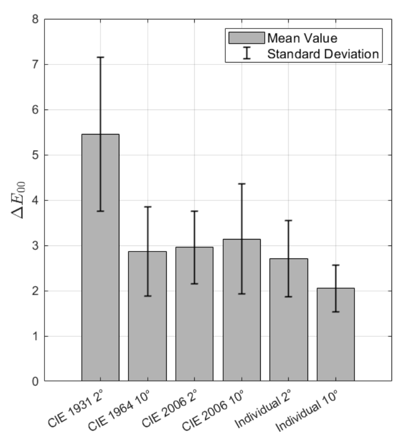


Figure 6 The CMFs' performance for the LEDSimulator experiment

Another way to look at the CMFs' performance is to plot the data presented in ellipses in a*b* plane. For each of the 15 colors tested, there are 3 ellipses, representing 1931 2º, CIE2006 10º CMF and ICMF 10o. All ellipses were transformed to have the same color Centre at CIE 2006 10º for easy comparison.

A smaller ellipse means a better CMF, i.e. observers to have a smaller variation. As it can be seen that the shape and orientation of the ellipses from the three CMFs are quite similar except those in the cyan region. The ICMF ellipses are always the smallest and the 1931 2º ellipses are always the largest, and the 2006 10º ellipses in the middle. The ellipse pattern in Figure 7 summarises the results quite clearly and agree well with those in Figure 6.

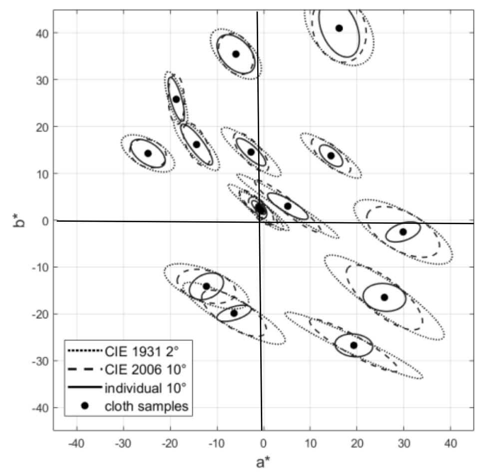


Figure 7 The experimental data presented in the form of ellipses for CIE 1931 2º, 2006 10º, individual 10º respectively.

5. Conclusion

For all the 4 experiments conducted here Cross-display, LEDSimulator, LEDMax 2º and LEDMax 10º, intra- observer variation is much smaller than inter-observer by about 200%,i.e. larger size will have less variation.

LEDSimulator can provide more accurate results (Inter 2.12; Intra 0.62 DEoo units), followed by LEDMax (2.04, 1.06), and less accurate for the displays (2.82, 1.14). However, the differences are small. Observer training has been realized to be an important issue.

Overall, ICMF clearly gave outstanding performance. The LEDMax system can accurately measure ICMF. This could pave the way for the revolution of colorimetry to consider individualized color reproduction.

To perform quality control using CIE 1931 2º could be detrimental as demonstrate by many researchers [8,9]. The present results are also support the replacement. CIE 2006 2º should be a good choose.

For the standard developments, the observer metamerism matric (OMM) can be used to judge the quality of a display. It can be used in conjunction with color gamut size to achieve not only large gamut but also observer consistency. The lager the OMM, the worse the color vision consistency between observers. Also, the long waiting standard deviate observer (SDO) can be developed to estimate the observer variation of a particular color specification.

Acknowledgements

National Natural Science Foundation of the Chinese government (61775190); Biotechnology and Biological Sciences Research Council, UK (BB/Y011759/1).

6. References

[1] W. D. Wright, "A re-determination of the trichromatic coefficients of the spectral colors," *Transactions of the Optical Society,* vol. 30, no. 4, p. 141, 1929.

[2] W. D. Wright, "A re-determination of the mixture curves of the spectrum," *Transactions of the Optical Society,* vol. 31, no. 4, p. 201, 1930.

[3] J. Guild, "The colorimetric properties of the spectrum," *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character,* vol. 230, no. 681-693, pp. 149–187, 1931.

[4] W. S. Stiles and J. M. Burch, "NPL color-matching investigation: final report (1958)," *Optica Acta: International Journal of Optics,* vol. 6, no. 1, pp. 1–26, 1959.

[5] CIE, "Fundamental Chromaticity Diagram with Physiological Axes – Part 1," 2006.

[6] CIE, "Fundamental Chromaticity Diagram with Physiological Axes – Part 2: Spectral Luminous Efficiency Functions and Chromaticity Diagrams," 2015.

[7] A. Stockman and L. T. Sharpe, "Cone spectral sensitivities and color matching," *Color vision: From genes to perception,* pp. 53–88, 1999.

[8] J. Wu, M. Wei, Y. Fu, and C. Cui, "Color mismatch and observer metamerism between conventional liquid crystal displays and organic light emitting diode displays," *Opt. Express,* vol. 29, no. 8, pp. 12292–12306, 2021.

[9] K. Shi and M. R. Luo, "Factors affecting color matching between displays," *Opt. Express,* vol. 30, no. 15, pp. 26841–26855, 2022.

[10] K. Shi, M. R. Luo, A. T. Rider, T. Huang, L. Xu, and A. Stockman, "A multi-primary trichromator to derive individual color matching functions and cone spectral sensitivities," *Color Research & Application,* vol. 49, no. 5, pp. 449-464, 2023.

[11] K. Shi, M. R. Luo, A. T. Rider, S. Song, T. Huang, and A. Stockman, "Individual differences in color matches and cone spectral sensitivities in 51 young adults," *Opt. Express,* vol. 32, no. 13, pp. 23597–23616, 2024.

[12] K. Shi, M. R. Luo, A. T. Rider, S. Song, T. Huang, and A. Stockman, "Individual color matches and cone spectral sensitivities in 100 observers of varying age," *Optics Express in press*2024.

[13] A. Stockman and A. T. Rider, "Formulae for generating standard and individual human cone spectral sensitivities," *Color Research & Application,* vol. 48, no. 6, pp. 818–840, 2023.

[14] M. R. Luo, G. Cui, and B. Rigg, "The development of the CIE 2000 color-difference formula: CIEDE2000," *Color Research & Application,* vol. 26, no. 5, pp. 340–350, 2001.

[15] D. L. Long and M. D. Fairchild, Modeling observer varability and metamerism failure in electronic color displays, Journal of Imaging Science， 030402-1-14 2014.