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Observer metamerism to display white point between LCD and OLED displays

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Abstract

Displays with different primary sets were found to introduce perceived color mismatch between pairs that are computationally metameric and to affect the degree of observer metamerism. OLED display is becoming more and more popular than LCD display in different imaging systems. In this study, human observers used an LCD and eight OLED displays to match the color appearance of a D 70 white stimulus produced by a spectrally tunable LED device. It was found the chromaticities of the LCD display were significantly different from those of the OLED displays to achieve a match. When the colors were adjusted to have matched appearance, the chromaticities of the OLED displays were always shifted towards closer to the blackbody locus using the CIE 1931 Color Matching Functions (CMFs). The results also suggested that the CIE 2006 2° Color Matching Functions had the best performance.

Introduction

Color gamut is a critically important characteristic for a display, which decides the range of colors that can be rendered, with a larger color gamut for producing a wider range of colors. Changing color gamut requires to change the chromaticities of the primaries, with the chromaticities closer to the spectrum locus producing a larger gamut [1-4]. Changing the chromaticities of the primaries, however, does not only happen with the change of color gamut. Displays with similar color gamut may have different primaries.

Though changing the primary set should not be expected to introduce color mismatch, since the color matching data should be easily transformed between different primary sets and the stimuli having the same chromaticities should visually match in color [6] according to Grassmann's laws [5]. Various psychophysical studies, however, suggested the failure of color match using different primary sets [7-13], which was fundamentally caused by the failure of Grassmann's laws. Two color stimuli with the same chromaticities but different primary sets were found to have different perceived color appearance, or two stimuli having matched perceived color appearance using different primary sets were found to have different chromaticities. Moreover, changing the primary set was also found to cause observer metamerism [14-18]. A pair of color stimuli produced using two primary sets which are visually matched to one observer may be mismatched to other observers. It was found that the degrees of observer metamerism (i.e., the variations of color differences perceived by different observers) varied with the primary sets.

The four CIE Color Matching Functions (CMFs)—CIE 1931 2°, CIE 1964 10°, CIE 2006 2°, and CIE 2006 10°—characterize the color match of an average color-normal observer. Variations in CMFs have been found among individuals due to various factors, such as lens optical density, macular pigment optical density, and photopigment optical density. In 2015, Asano proposed an individual colorimetric observer model [19] based on the CIE 2006 physiological observer model. The individual colorimetric observer model characterizes the possible variations caused by eight physiological parameters, together with age and FOV, to derive the individual cone fundamentals and CMFs.

OLED displays are gradually replacing conventional LCD displays for imaging systems in recent years. Though color mismatches, especially for neutral colors, were found to happen between LCD and OLED displays, few studies have investigated this through psychophysical experiments. In this study, we investigated the metamerism issues caused by the different displays, including an LCD display and eight OLED displays through a color matching experiment.

Experiment setup

Apparatus

The experiment was carried out using a light booth with dimensions of 60 cm (width) × 60 cm (depth) × 60 cm (height). The interiors of the viewing booth were painted using Munsell N8 paint. Two 5 cm × 5 cm openings, with a distance of 6 cm between them, were cut at the center of the back panel. An 11-channel spectrally tunable LED device was placed behind the left opening. A smart phone that was fixed on a tripod was placed behind the right opening. In total, nine smart phones, including one LCD display (i.e., No. 2) and eight OLED displays, were used in the experiment. These eight OLED displays were from three different manufacturers. Figure 1 shows the SPDs of the nine displays at their default white point (i.e., RGB values were set to 255). Obvious differences can be observed between LCD and OLED displays, while there were still small differences among the OLED displays.

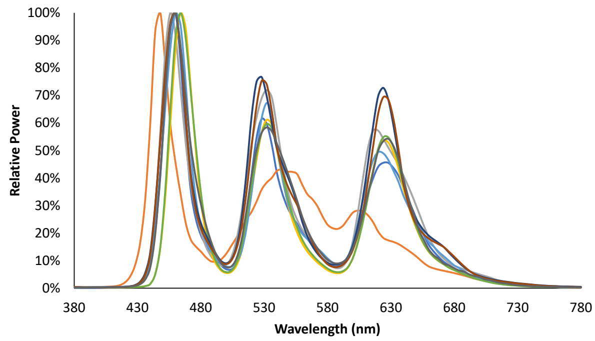

Figure 1 SPDs of the refernece stimulus and the eight primaries at the full intensity.

A chin rest was mounted just outside the viewing booth, so that each stimulus occupied a field of view (FOV) around 4.77° and the viewing angle between the two stimuli was around 5.72°, which allowed the observers to view the two simultaneously during the experiment.

Display calibration and color matching

The reference stimulus produced by the spectrally tunable LED device was calibrated to simulate a D70 illuminant, with the SPDs shown in Figure 1, which was measured using a calibrated PhotoResearch PR-655 spectroradiometer. The chromaticities derived using the measured SPDs were (0.3047, 0.3229) using the CIE 1931 2° CMFs and the luminance was 300 cd/m^2.

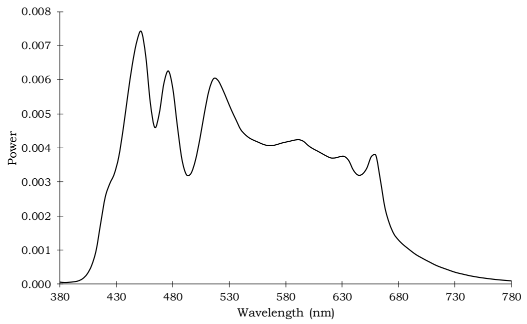

Figure 2 SPDs of the refernece stimulus and the eight primaries at the full intensity.

The nine displays were calibrated using a 3D Look-up-Table (LUT) at the nominal luminance at 300 cd/m^2, with the RGB values derived for a step of 0.0015 unit along *u*' and *v*' directions. A customized program was then developed to adjust the chromaticity along the *u*' and *v*' axes in the CIE *u*'*v*' chromaticity diagram using the four arrow keys on a wireless keyboard. The accuracy of the LUT was verified by comparing the chromaticities of 20 color stimuli predicted by the LUT and derived using the measured SPDs based on the RGB inputs, as shown in Figure 3.

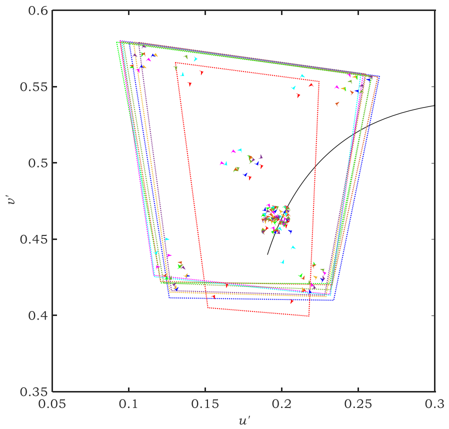

Figure 3 Chromaticities of the 20 color stimulus predicted by the LUT and derived using the measured SPDs based on the RGB inputs for each of the nine displays.

During the experiment, the observers used the four arrow keys to adjust the color appearance of the display until the it matched to the color appearance of the reference stimulus. The adjustment always started at the chromaticities of (0.183, 0.475), which had an obvious color difference from the reference stimulus. The observer was allowed to take as much time as he or she needed, and confirmed the color match by pressing the *Enter* key on the keyboard. The program recorded the RGB values of the color that was confirmed to have the matched color appearance as the reference stimulus.

Each observer performed the color match using each of the nine displays, and three OLED displays (i.e., No. 1, 3, and 5) were matched twice for characterizing the intra-observer variations. In total, seven observers completed the experiment.

Results and discussions

Observer variations

The inter- and intra-observer variations were characterized using Mean Color Difference from Mean (MCDM) in the CIE 1976 *u*'*v*' diagram. The intra-observer variation was evaluated using the differences between the chromaticities that were adjusted by each observer twice using the same display, which resulted in the MCDM values between 0.0004 and 0.0024, with a mean of 0.0014 in *u*'*v*' units. The inter-observer variation was evaluated using the differences between the chromaticities adjusted by each observer and the average chromaticities adjusted by all the observers (i.e., an average observer) for display with a mean MCDM values of 0.0031 in *u*'*v*' units. Both the intra- and inter-observer variations were comparable to past studies.

Chromaticities of the adjusted stimuli

Figure 4 shows the (*u*',*v*') chromaticities, together with the one-standard-error ellipeses, of the stimuli that were adjusted to have the same color appearance as the reference stimulus. These chromaticities were calculated using the CIE 1931 2° CMFs. If the CMFs were able to accurately characterize the color matches between the reference and matching stimuli, the chromaticity difference between the reference stimulus and the center of the ellipses should be zero. The smaller the difference, the better the performance of the CMFs.

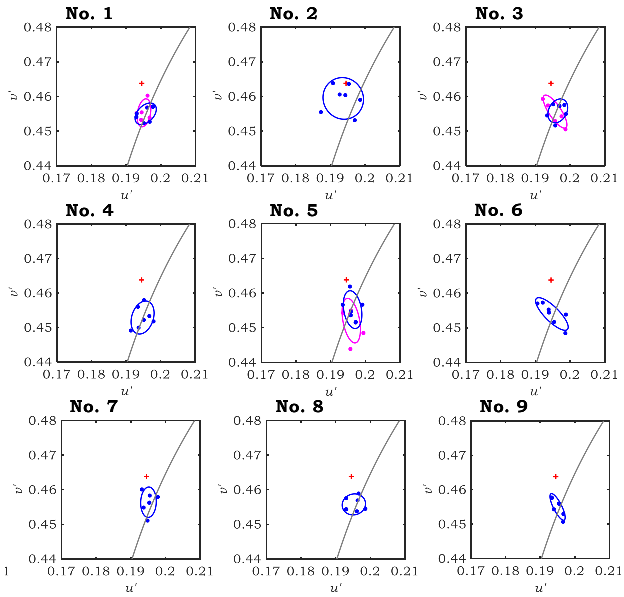

Figure 4 (u',v') chromaticities, together with the one-standard-error ellipeses, of the stimuli that were adjusted to have the same color appearance as the reference stimulus. These chromaticities were calculated using the CIE 1931 2°CMFs. The red cross is the chromaticities *of the reference stimulus. The two sets of datapoints and ellipses for No. 1, 3, and 5 are the repeated adjustments made by each observer.*

It can be observed that only for the LCD display (i.e., No 2), the chromaticities of the reference stimulus were in the ellipse. For all the OLED displays, the chromaticities of the reference stimulus were always outside the ellipses. This clearly reveals that the CIE 1931 CMFs cannot be used to characterize the color matches between the OLED displays and the reference stimulus. Moreover, in comparison to the chromaticities of the reference stimulus, the ellipses of the OLED displays were closer to the blackbody locus. This suggests that if the OLED displays were calibrated to have the same chromaticities as the reference stimulus, the displays would appear to have a green tint. Such a green tint appearance can be reduced by shifting the chromaticities towards the blackbody locus.

Comparisons among the CMFs

The chromaticities and the ellipses were also calculated using the other three commonly used CMFs (i.e., CIE 1964 10°, CIE 2006 2°, and CIE 2006 10°), with Figure 5 shows the one-standard error ellipses.

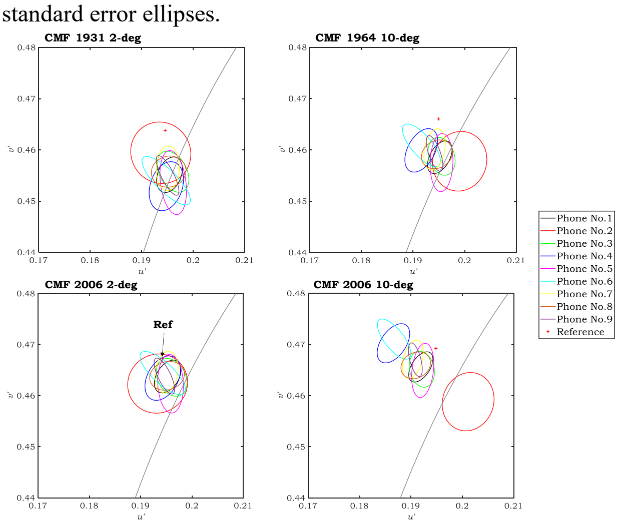

Figure 5 One standard error ellipses fitted using the chromaticites of the adjusted stimuli, and the chromaticities of the reference stimulus using the four different CMFs. (Note: the chromaticities of the reference stimulus is highlighted in the CIE 2006 2° CMFs figure)

It can be observed that the ellipses for the eight OLED displays were overlapped to each other when the CIE 1931 and 2006 2° CMFs were used. When the LCD display was considered, all the nine ellipses were overlapped only when the CIE 2006 2° CMFs were used. Though the chromaticities of the reference stimulus were not strictly located at the center of all the ellipses, they were much closer to the nine ellipses. This suggested that the CIE 2006 2° CMFs had the best performance in predicting and characterizing the color matches using these eight OLED and the one LCD displays.

Though many past studies have suggested the better performance of 10° CMFs in predicting the perceived color appearance [20], the better performance of the CIE 2006 2° CMFs could be due to the fact that the size of the stimuli was only 4.77°. This was similar to the findings in a recent study [21].

Conclusion

A psychophysical experiment was carried out to investigate the metamerism between LCD and OLED displays. Human observers adjusted the color appearance of nine displays, including one LCD and eight OLED displays from different manufacturers, to match the color of a reference stimulus simulating the CIE D70 illuminant using a spectrally tunable LED device. The stimuli had a field of view of 4.77°. The CIE 1931 2° CMFs were found to have a good performance in characterizing the color matches between the LCD display and the reference stimulus. The color matches between the OLED displays and the reference stimulus, however, cannot be characterized by the CIE 1931 2° CMFs. The chromaticities of the stimulus produced by the OLED displays were shifted towards the blackbody locus. This suggested that the OLED displays would have a green tint if their chromaticities matched to the reference stimulus using the CIE 1931 2° CMFs. Among the four widely used CMFs (i.e., CIE 1964 10°, CIE 2006 2°, and CIE 2006 10°), the CIE 2006 2° CMFs were found to have the best performance, which could be due to the relative small size of the stimuli.

Reference

1. ITU-R Recommendation BT.709-5, "Parameter values for the HDTV standards for production and international programme exchange," 2002.
2. Adobe Systems Inc., "Adobe RGB (1998) color image encoding," 2005.
3. SMPTE RP 431-2, "D-cinema quality – reference projector and environment," 2011.
4. ITU-R Recommendation BT.2020, "Parameter values for ultra-high definition television systems for production and international programme exchange," 2012.
5. G. Wyszecki and W. S. Stiles, Color Science: Concepts and Methods, Quantitative Data and Formulae, 2nd Edition (Wiley 1982).
6. J. Schanda, Colorimetry: Understanding the CIE System (Wiley 2007).
7. J. Fang and Y. J. Kim, "A Matrix-based method of color correction for metamerism failure between LCD and OLED," SID 2018 Digest, 1044-1047 (2018).
8. J. Li, P Hanselaer, and K. A. G. Smet, "The impact of color matching primary peak wavelength on color matching accuracy and observer variability," in Proceedings of the 27th Color and Imaging Conference (2019), pp. 220-224.
9. B. Bodner, N. Robinson, R. Atkins, and S. Daly, "Correcting metameric failure of wide color gamut displays," SID 2018 Digest, 1040-1043 (2018).
10. K. W. Houser and X. Hu, "Visually matching daylight fluorescent lamplight with two primary sets," Color Res. Appl. 29(6), 428-437 (2004).
11. A. David, D. Sahlhoff, and M. Wisser, "Human perception of light chromaticity: short-wavelength effects in spectra with low circadian stimulation, and broader implications for general LED sources," Opt. Express 27(22), 31553-31566 (2019).
12. B. Oicherman, M. R. Luo, B. Rigg, and A. R. Robertson, "Adaptation and color matching of display and surface colors," Color Res. Appl. 34(3), 182-193 (2009).
13. A. Sarkar, L. Blonde, P. L. Callet, F. Autrusseau, P. Morvan, and J. Stauder, "A color matching experiment using two displays: design considerations and pilot test results," In Proceedings of the 5th European Conference on Color in Graphics, Imaging and Vision (2010), pp. 414-422.
14. Y. Asano, M. D. Fairchild, L. Blonde, and P. Morvan, "Color matching experiment for highlighting interobserver variability," Color Res. Appl. 41(5), 530-539 (2016).

15. M. D. Fairchild and R. L. Heckaman, “Measuring observer metamerism: the nimeroff approach,” Color Res. Appl. 41(2), 115-124.
16. H. Xie, S. P. Farnand, and M. J. Murdoch, “Observer metamerism in commercial displays,” J. Opt. Soc. Am. A 37(4), A61-A69.
17. D. L. Long and M. D. Fairchild, “Modeling observer variability and metamerism failure in electronic color displays,” in Proceedings of the 22nd Color and Imaging Conference (2014), pp. 14-27.
18. B. Oicherman, M. R. Luo, B. Rigg, and A. R. Robertson, “Effect of observer metamerism on color matching of display and surface colors,” Color Res. Appl. 33(5), 346-359.
19. Y. Asano, “Individual colorimetric observers for personalized color imaging,” PhD dissertation at Rochester Institute of Technology (2015).
20. K. W. Houser, M. Wei, A. David, and M.R. Krames, “Whiteness perception under LED illumination,” LEUKOS 10(3), 165-180.
21. Y. Hu, M. Wei, M. R. Luo, “Observer metamerism to display white point using different primary sets,” Opt. Express 28(14), 20305-20323.

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