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Defining D65 white point chromaticities for wide color gamut displays using different color matching functions

Zheng Huang and Minchen Wei*, The Hong Kong Polytechnic University
minchen.wei@polyu.edu.hk

Abstract
White point chromaticities play an important role in display specifications and calibrations, with the D65 chromaticities widely used in various standards. Such a D65 chromaticities are calculated and specified with the CIE 1931 2° color matching functions (CMFs). Though it is well known that wide color gamut displays always introduce color shifts (i.e., the same D65 chromaticities result in shifted color appearance) and other CMFs were found to have better performance, there is no guidelines about how the D65 white point chromaticities should be shifted. A color matching experiment was carried out in this study, in which 12 displays were used to match the color appearance of a broadband D65 reference. The results can be used as a reference when defining the D65 white point chromaticities using different CMFs.

Introduction
Chromaticities, which are calculated using the spectral composition and the color matching functions (CMFs), are used for display calibrations and specifications, with stimuli calibrated to the same chromaticities expected to have the matched color appearance. White point chromaticities and color gamut chromaticities are particularly critical, as they affect the perceived color appearance and the range of the colors that can be shown on a display.

It is widely known that the same chromaticities sometimes do not result in the same appearance, which is mainly due to the effect of the spectral compositions on the CMFs. In particular, stimuli with narrower spectral compositions are more likely to introduce color mismatches. With the popularity of displays with a wider color gamut, this is becoming extremely critical. Great efforts have been made to investigate how the spectral compositions and the size of the stimuli affect the color mismatch and which CMFs have better performance [1-5]. Based on the findings, manufacturers can use a different CMF set or a different sets of target chromaticities when calibrating the displays, which allows consistent color appearance among different products. Such solutions, however, introduce a challenge to display specifications, including the white point and color gamut.

Display specifications are commonly performed based on the chromaticities calculated using the CIE 1931 2° CMFs [6]. For example, the D65 white point chromaticities are specified using the CIE 1931 2° CMFs in the International Telecommunication Union (ITU) standards BT.709-6 [7], BT.2020-2 [8], and BT.2100-2 [9]. Though changing the CMFs or target chromaticities for display calibration can produce consistent color appearance, it also makes the displays fail to satisfy these standards. More importantly, the D65 chromaticities are the chromaticities of a standard 6500 K daylight illuminant, which does not exist in reality. Therefore, the industry are eager to understand how does a D65 white point should look like, and whether it is necessary to specify a new set of D65 white point chromaticities for different CMFs.

With the above in mind, a color matching experiment was carried out. In particular, a multi-channel LED device was used to produce reference stimuli with the D65 chromaticities as calculated using the CIE 1931 2° CMFs. These stimuli were expected to have similar appearance as a standard D65 illuminant, since they had broadband spectra. Twelve displays, including 11 OLED and one LCD, were used to produce test stimuli.

Methods

Apparatus and setup
An apparatus that was designed and built by the us [4] was used in this experiment. It allows the reference and test stimuli to be placed next to each other, as shown in Figure 1, with the reference stimulus shown at the bottom and the test stimulus shown at the top. Both the reference and test stimuli had a size of 10 cm × 5.5 cm. A chin rest was fixed on the table, so that the observer viewed the stimuli at a distance of 42 cm and the stimuli occupied an FOV around 14°.

Figure 1 Photograph of the stimuli viewed by the observer during the experiment.

A 14-channel spectrally tunable LED device was placed behind the apparatus to produce the reference stimuli, and 12 displays of smartphones, tablets and PCs were placed above apparatus to produce the test stimuli. These 12 displays were carefully selected from 30 displays to vary the spectral compositions, with the spectra of the primaries shown in Figure 2 and the color gamut calculated using the CIE 1931 2° CMFs shown in Figure 3. It can be observed that the color gamuts were generally greater than the P3 color gamut.

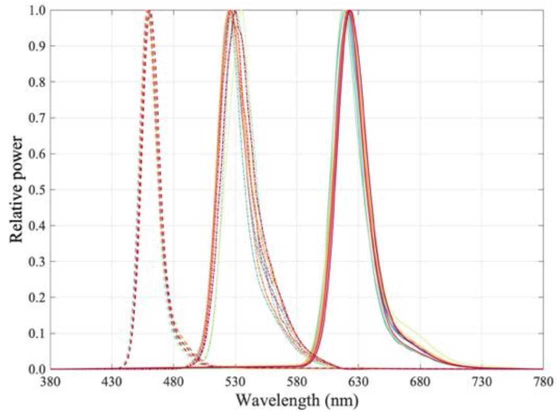

Figure 2 Spectral power distribution of the primaries of the twelve displays used to produce the test stimuli.

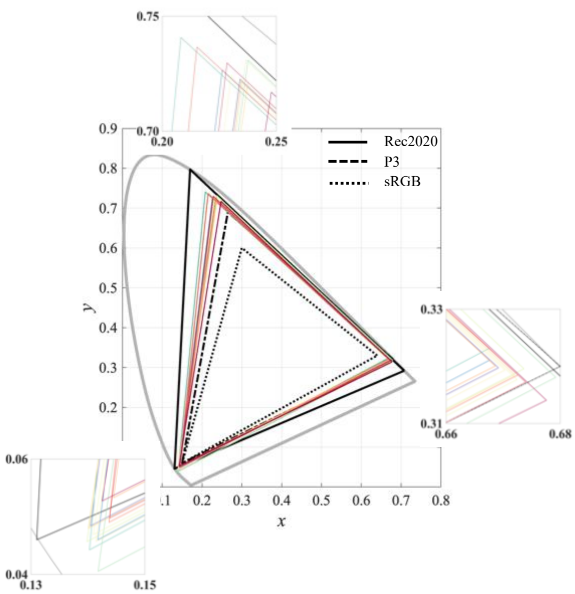

Figure 3 Color gamut of the twelve displays as calculated using the CIE 1931 2° CMFs.

Stimuli and calibration

The intensities of the 14 channels of the LED device were carefully adjusted to produce stimuli that can be considered similar to a standard D65 illuminant [6]. Two reference stimuli were calibrated using the CIE 1931 2° CMFs, with the luminance of 111 and 388 cd/m^2 and (u',v') chromaticities of (0.1976, 0.4681) and (0.1976, 0.4676) as measured using a Specbos 1811 spectroradiometer. Figure 4 shows the measured spectral power distributions (SPDs) of the two reference stimuli.

The displays were calibrated using a gain-offset-gamma (GOG) model to build the relationship between the display RGB values and the tristimulus values XYZ. Then images with solid colors whose chromaticities can uniformly cover the reference chromaticities in the CIE 1976 $u'v'$ chromaticity diagram were produced and sent into the smartphones and tablets for producing the test stimuli, with the backlight intensity used to adjust the stimuli luminance around the reference stimuli luminance. During the experiment, the observer used the arrow keys on a keyboard to change the color appearance of the test stimulus by switching the images, with the four directions along the u' and v' axes in the CIE 1976 $u'v'$ chromaticity diagram (i.e., $+u'$ for red, $-u'$ for green, $+v'$ for yellow, and $-v'$ for blue), with each adjustment corresponding to around 0.0015 unit of $u'v'$.

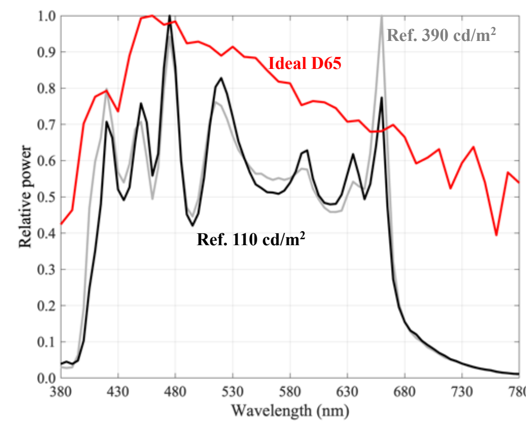

Figure 4. Measured spectral power distributions of the two reference stimuli, together with the standard D65 illuminant.

Observers and experimental procedure

Eleven observers (4 females and 7 males) aged between 22 and 37 years (mean = 27, standard deviation = 4.14) participated in this experiment. All observers had normal color vision, as evaluated by the Ishihara Color Vision Test.

Upon arrival, the observer was asked to complete a general information survey and the Ishihara Color Vision Test. After that, the observer was guided to the apparatus, and the general illumination in the room was turned off. The experimenter then explained how to use the four arrow keys on the keyboard (right: $+u'$, left: $-u'$, up: $+v'$, down: $-v'$) to adjust the color appearance of the test stimulus to match the color appearance of the reference stimulus. The observer was asked to maintain their chin on the rest throughout the experiment, and he or she was allowed to take as much time as he or she needed for each match. After he or she confirmed the adjustment, he or she pressed the enter key to proceed to the next adjustments. The initial chromaticities of the test stimulus were purposely to be quite different from those of the reference stimulus, so that the observers always need to make the adjustment for producing a matched appearance.

Each observer made 25 adjustments in total, with two adjustments for 11 displays, one adjustment for laptop (note: the laptop cannot reach 390 cd/m^2), and two repeated adjustments for one smartphone display for evaluating intra-observer variations. All the displays were switched on for a least 30 minutes before the experiment for stabilization.

Results and discussions

The spectral power distributions of the final image that were selected by each observer for each match was measured again after the experiment for accurately characterizing the color matches performed by the observer.

Intra- and inter-observer variations

The mean color difference from the mean (MCDM) in the CIE 1976 *u'v'* chromaticity diagram using the CIE 1931 2° CMFs were used to characterize the intra- and inter-observer variations. The intra-observer variations were characterized based on the differences between the chromaticities of the repeated adjustments and the average chromaticities. The MCDM values ranged between 0.0009 and 0.0091, with a mean of 0.0057, at the luminance of 110 cd/m², and between 0.0020 to 0.0053, with a mean of 0.0046, at the luminance of 390 cd/m². The inter-observer variations were characterized based on the differences between the chromaticities adjusted by each observer and the average chromaticities adjusted by all observers (i.e., the average observer). The MCDM values ranged between 0.0027 and 0.0054, with a mean of 0.0037. Both the intra- and inter-observer variations, in terms of MCDM values, were comparable to those in recent color matching experiments [4, 5], suggesting the reliability of the experiment results.

Performance of the 12 CIE standard CMFs

The average chromaticities of the test stimuli adjusted by the observers for the 12 displays, together with the one-standard-deviation error ellipses were calculated using 12 sets of the CIE CMFs, including the CIE 1931 2°, 1964 10° CMFs, and the CIE 2006 CMFs with the FOV set from 1° to 10°. Figures 5 to 8 show the results in the CIE u'v' chromaticity diagram using the four most commonly CMFs (i.e., the CIE 1931 2°, 1964 10°, 2006 2°, and 2006 10° CMFs).

It can be observed that the chromaticities of the reference stimuli, especially the one at 110 cd/m^2, were always very close to those of the standard D65 illuminant, which suggesting that the reference stimuli can be considered as proxies of a standard D65 illuminant.

The distributions of the adjusted chromaticities, in terms of the sizes and the orientations of the one-standard-deviation error ellipses, at the two luminance levels were generally similar. The slight shift is likely due to the slight difference between the two reference stimuli.

The distances between the ellipses and the reference stimuli were generally smaller in Figures 6 and 8 than those in Figures 5 and 7, suggesting the 10° CMFs had a better performance. This was likely due to the size of the stimuli were beyond 4°.

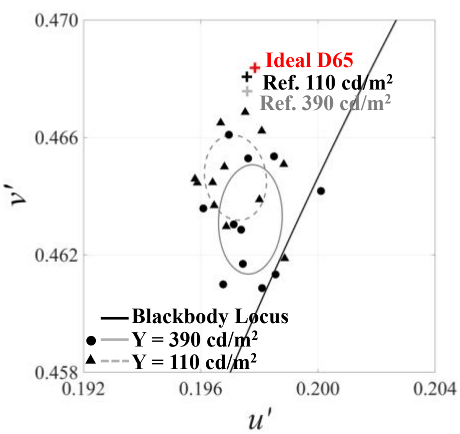

Figure 5 Average chromaticities of the stimuli adjusted by the observers using the twelve test displays, together with the fitted one-standard-deviation error ellipses, calculated using the CIE 1931 2° CMFs.

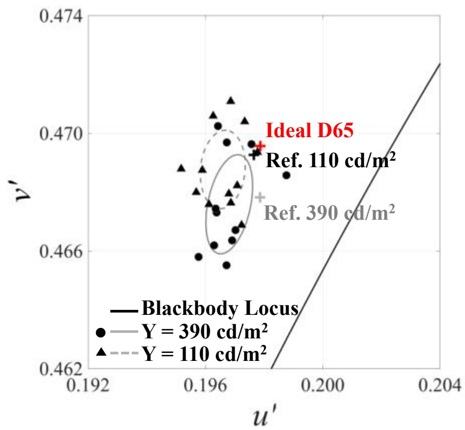

Figure 6 Average chromaticities of the stimuli adjusted by the observers using the twelve test displays, together with the fitted one-standard-deviation error ellipses, calculated using the CIE 1964 10° CMFs.

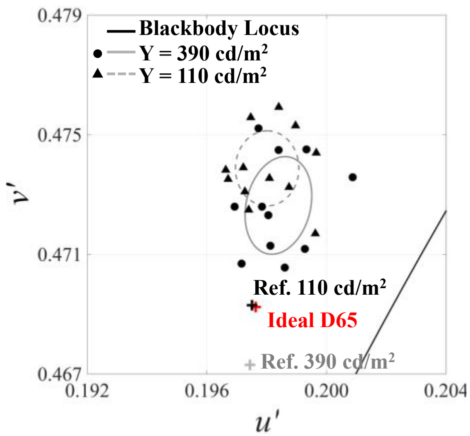

Figure 7 Average chromaticities of the stimuli adjusted by the observers using the twelve test displays, together with the fitted one-standard-deviation error ellipses, calculated using the CIE 2006 2° CMFs.

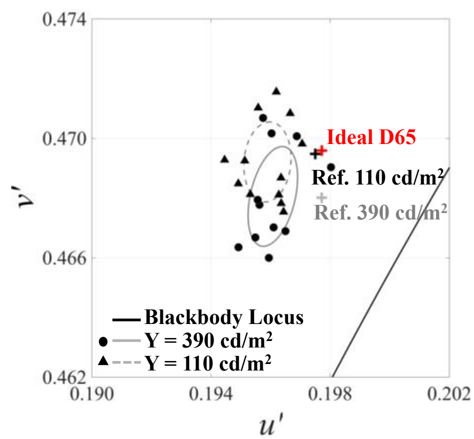

Figure 8 Average chromaticities of the stimuli adjusted by the observers using the twelve test displays, together with the fitted one-standard-deviation error ellipses, calculated using the CIE 2006 10° CMFs.

Among the 12 sets of the CMFs, the CIE 2006 7° CMFs were found to have the best performance, with the distances between the chromaticities of the adjusted test stimuli and those of the reference stimuli being the smallest. Figure 9 shows the results calculated using the CMFs. The FOV of 7° was around half of the stimuli size used in the experiment, which was consistent to the finding in a recent study [10].

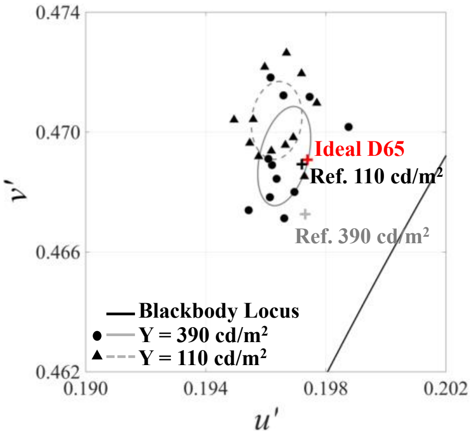

Figure 9 Average chromaticities of the stimuli adjusted by the observers using the twelve test displays, together with the fitted one-standard-deviation error ellipses, calculated using the CIE 2006 7° CMFs.

Specification of the D65 white point chromaticities using different CIE CMFs

The results presented above clearly suggested that the D65 chromaticities calculated using the CIE 1931 2° CMFs as specified in various standards cannot be used to calibrate wide color gamut displays, as they will produce color mismatches. This suggested the necessity to specify the D65 chromaticities using the different CIE CMFs for producing consistent appearance as a standard D65 illuminant. Table 1 summarizes the average chromaticities of the test stimuli adjusted by the observers at the two luminance levels using the 12 CIE CMFs. Since the reference stimulus at 110 cd/m^2 was more similar to the standard D65 illuminant, the chromaticities of the adjusted test stimuli at 110 cd/m^2 could be considered as specifications of the D65 white point.

Table 1. Summary of the average chromaticities of the test stimuli adjusted by the observers, which can be considered as specifications for producing same color appearance as a standard D65 illuminant.

CMFs	(u',v') at 390 cd/m^2	(u',v') at 110 cd/m^2
CIE1931 2°	(0.1977,0.4632)	(0.1972,0.4646)
CIE1964 10°	(0.1968,0.4676)	(0.1966,0.4688)
CIE2006 1°	(0.1979,0.4727)	(0.1975,0.4739)
CIE2006 2°	(0.1984,0.4726)	(0.1981,0.4739)
CIE2006 3°	(0.1974,0.4715)	(0.1971,0.4727)
CIE2006 4°	(0.1972,0.4709)	(0.1969,0.4721)
CIE2006 5°	(0.1970,0.4703)	(0.1967,0.4715)
CIE2006 6°	(0.1968,0.4698)	(0.1965,0.4710)
CIE2006 7°	(0.1966,0.4692)	(0.1964,0.4704)
CIE2006 8°	(0.1964,0.4687)	(0.1962,0.4698)
CIE2006 9°	(0.1962,0.4681)	(0.1961,0.4693)
CIE200610°	(0.1961,0.4681)	(0.1959,0.4692)

Conclusion

Great efforts have been made to investigate how to produce consistent color appearance across different displays. The specification of the D65 white point chromaticities is non-trivial, since all the standards simply specify the D65 white point chromaticities based on the standard D65 illuminant, which does not exist in reality, and the CIE 1931 2° CMFs. In this study, we used a 14-channel spectrally tunable LED device to create reference stimuli which can be considered as good proxies as the standard D65 illuminant. Twelve wide color gamut displays were used to carry out the color matching experiment. The results clearly suggested the necessity to specify the D65 white point chromaticities, and provided the recommended chromaticities using the twelve CIE CMFs.

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Author Biography

Zheng Huang is a PhD student at the Hong Kong Polytechnic University. He obtained his BSc and MSc degrees at Wuhan University.

Minchen Wei is a professor at The Hong Kong Polytechnic University. He obtained his BEng degree at Fudan University, and MSc and PhD degrees at The Pennsylvania State University. His research interests mainly cover color science and imaging science.