

Does D65 illuminant or D65 chromaticities produce neutral white appearance?

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Abstract

D65 plays a critical role in color reproduction, specification, and characterization. Displays commonly use D65 chromaticities as the white point, but many studies shown that a stimulus produced by displays having a slightly higher CCT was perceived to produce neutral white appearance. Moreover, our two recent studies found LCD/OLED displays need to produce a stimulus having a slightly higher CCT to match the appearance of a high quality D65 illuminant that was produced by a 14 channel spectrally tunable LED device. We hypothesize that a higher CCT required by displays to produce a neutral white appearance was caused by the CIE 1931 Color Matching Functions and a D65 illuminant can indeed produce a neutral white appearance. In this study, we use the 14 channel LED device to produce a series of high quality daylight simulators. The observers generally selected the stimulus having a CCT between 6346 and 6906 K to produce the neutral white appearance. When using an LCD display to match the color appearance of the selected stimulus, the average CCT was between 7209 and 7943 K. Such a finding suggests the importance of color matching functions in display specification and calibration.

Introduction

D65 chromaticity coordinate is important in color science. On one hand, it is commonly adopted as the white point for display calibration and specification. For example, various color gamuts (e.g., Rec 709, P3, and Rec 2020) are specified with the white point of D65. On the other hand, it is widely used as the chromaticity coordinate of a viewing or an adapting condition for color specification or evaluation. For example, the CIELAB color space was developed for a D65 viewing condition, and various color scales (e.g., whiteness, Munsell) are developed for specifying colors under a D65 illumination. All of these D65 chromaticities, however, are actually the chromaticities of the CIE standard D65 illuminant calculated with the CIE 1931 color matching functions (CMFs). If the calculations use a different set of CMFs, the chromaticity coordinates would change.

In 2024, Huang and Wei [1] carried out an experiment, in which they used a spectrally tunable LED device to produce a broadband source simulating the CIE standard D65 illuminant. The chromaticities of the source were calibrated to be very similar to those of the CIE standard D65 illuminant calculated using 12 different CMFs. Therefore, the color appearance of the source can be considered very similar to that produced by the CIE standard D65 illuminant, though the spectral power distributions were not identical. The observers then adjusted the color appearance produced by different displays to match the color appearance of the source. It was found that the chromaticities of the colors matched by the observers generally

shifted towards the direction of a higher CCT along the blackbody locus.

On the other hand, many studies in the recent years found that the observers adjusted the displays to a higher CCT for producing a neutral white appearance. For example, the displays or tablets were adjusted to 7300, 7924, 7200 K in Choi and Suk [2], Huang and Wei [3], and Li and Wei [4], and the OLED displays were adjusted to 7300 and 8900 K in Hu [5], and 7600 to 7900 K in Gao et al [6].

This made us wonder whether the higher CCT found in Huang and Wei [1] and the higher CCT found in these studies focusing on neutral white are related. In other words, whether displays with narrowband spectra need to adjusted to a higher CCT for producing a neutral white and also match the color appearance of the CIE standard D65 illuminant.

Therefore, we hypothesize that a source having a broadband spectrum can produce the neutral white appearance with the D65 chromaticities, and a source with a narrow band spectrum needs to have a higher CCT correspondingly. To test such a hypothesis, a series of sources with broadband spectra were calibrated to different CCT levels. The observers selected the source that can produce the neutral white appearance. Then the observers adjusted the color appearance of an LCD display to match that of the selected source.

Method

Apparatus and setup

To produce sources with broadband sources, a multichannel spectrally tunable LED device was used, which was the same as the one used in Huang and Wei [1]. A commercially available LCD tablet was used for the color matching task.

A customized apparatus was used to present the stimuli to the observers, with the LED device placed above the apparatus and the tablet placed behind the device. Therefore, the top stimulus was produced by the LED device, while the bottom stimulus was produced by the LCD tablet, as shown in Figure 1. A chin rest was mounted in front of the viewing opening, so that the two stimuli occupied a field-of-view around 14° and all the observers experienced the similar viewing geometry.



Figure 1 The two stimuli, with the top produced by the LED device and the bottom produced by the LCD display, viewed by the observers during the experiment.

Stimuli produced by the LED device

Twenty stimuli were carefully calibrated using a JETI specbos 1211 UV spectroradiometer by carefully adjusting the intensities of the LED channels in the device, aiming to produce sources that were simulating the standard CIE Daylight illuminants with the chromaticity differences $\Delta u'v'$ smaller than 0.004 using the four CIE standard CMFs (i.e., 1931, 1964, 2006 2° and 2006 10°) at a luminance of 100 cd/m². These 20 stimuli were calibrated to have a CCT from 5000 to 10,000 K, which was believed to be wide enough to produce a natural white appearance. Since CCT is not a uniform scale, the stimuli were calibrated to have an equal difference of 1/CCT. Figure 2 shows the chromaticity distribution of the 20 stimuli in the CIE 1976 $u'v'$ chromaticity diagram calculated using the CIE 1931 CMFs ; Figure 3 shows the spectral power distributions of the stimuli.

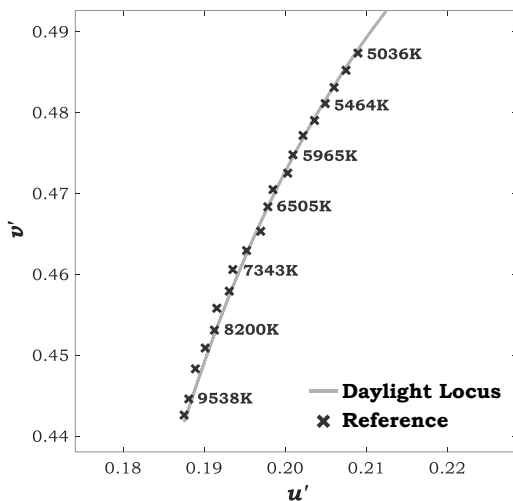


Figure 2 Chromaticity distribution of the 20 calibrated stimuli simulating the standard CIE daylight illuminants in the CIE 1976 $u'v'$ chromaticity diagram.

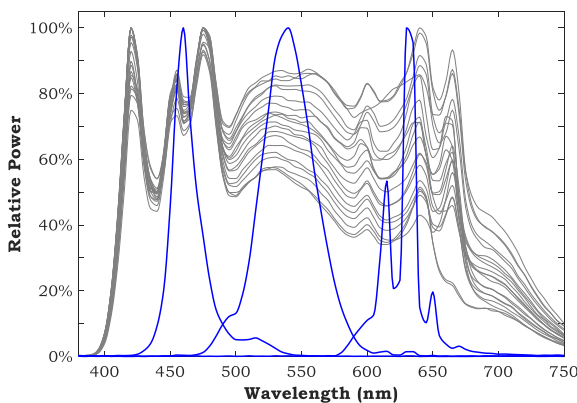


Figure 3 Relative spectral power distributions of the 20 calibrated stimuli simulating the standard CIE daylight illuminants and that of the LCD tablet's primaries.

Calibration of the tablet

The tablet was calibrated using a gain-offset-gamma model. The adjustment of the color was made using the four arrow keys on a keyboard, which shifts the chromaticities along the u' and v' axes in the CIE 1976 $u'v'$ chromaticity diagram with a step of 0.0015 $\Delta u'v'$ unit at a fixed luminance level (i.e., $+u'$ direction for red; $-u'$ direction for green; $+v'$ direction for yellow; $-v'$ direction for blue).

Experimental procedure and observers

Upon arrival, the observer completed the information survey and the Ishihara Color Vision Test, and then was seated in front of the apparatus. Then the top stimulus was switched to the stimulus with the highest or lowest CCT, and the tablet display was switched off. The observer was asked to use the two arrow keys to change the top stimulus until it appeared the neutral white, and the observer was allowed to switch back and forth among the stimuli without any time limitation. When he or she confirmed the selection, the observer pressed the Enter key. After that the tablet display was switched on, and the observer was asked to adjust the color appearance of the bottom stimulus to match that of the top stimulus using the four arrow keys. Again, there was no time limitation for the adjustment and the observer was asked to press the enter key to confirm his or her adjustment. Each observer completed two sessions, with the top stimulus started from the highest CCT in one session and from the lowest CCT in the other session, which helped to counter a possible directional bias. The order of these two sessions was randomized among the observers.

Ten observers between 26 and 35 years of age completed the experiment. All observers had normal color vision, as tested by the Ishihara Color Vision Test.

Results and discussion

After the experiment, the spectral power distributions of all the stimuli matched by the observers were measured using the spectroradiometer. All the analyses below were performed using the CIE 1931 2° CMFs.

Figure 4 shows the boxplots of the CCT values of the stimuli selected and matched by the observers, which can generally illustrate the range of the selections. It can be noticed that the starting point of the selections (i.e., from the highest or the lowest CCT) had a little effect on the judgments, with the starting point of the lowest CCT generally resulting in the selections to have a lower CCT values. More importantly, the average CCT of the matched stimuli of the LCD tablet were generally higher than the selected stimuli of the broadband source.

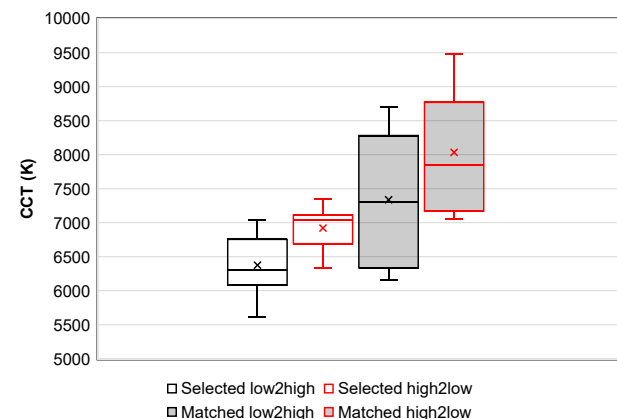


Figure 4 Boxplot of the CCT values of the stimuli selected and matched by the observers.

The information presented in Figure 4, however, may not be considered accurate, since CCT is not a uniform scale. Thus, we calculated the reciprocal value of the average CCT⁻¹ of the stimulus selected by the observers (i.e., $1/[(\sum CCT^{-1})/n]$), with the results of 6346 and 6906 K for the starting point of the lowest and highest CCT respectively. Moreover, the color matching task was performed in the two-dimensional plane (i.e., u^*v^* chromaticity diagram), a 95% confidence ellipses was fitted. Figure 5 shows the results in the CIE 1976 u^*v^* chromaticity diagram. In general, the differences between the selected and matched stimuli were similar to those presented in Figure 4. More interestingly, the chromaticity shifts of the LCD tablets towards the $-u^*-v^*$ direction were similar to those of the OLED displays in Huang and Wei [1].

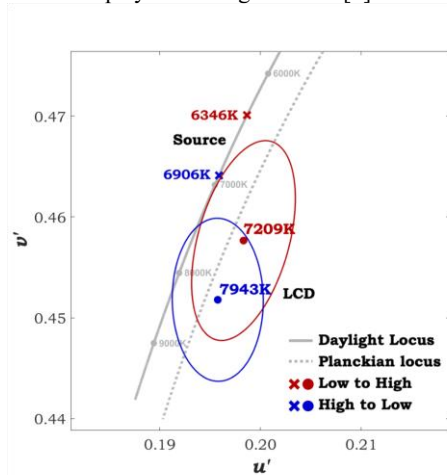


Figure 5 Results of the selected and matched stimuli, characterized using the reciprocal value of the average CCT⁻¹ and the average chromaticities, in the CIE 1976 u^*v^* chromaticity diagram.

The results presented above, together with other studies [1-6], clearly suggest that a broadband stimulus with a CCT around 6500 K was perceived to have the neutral white appearance, while a display (i.e., LCD or OLED) needs to have a CCT beyond 6500 K to be perceived to have the neutral white appearance.

Conclusion

Various studies in recent years found that displays need to have a CCT higher than 6500 K for producing the natural white appearance. Meanwhile, we found that observers adjusted the

displays to a CCT higher than 6500 K to match the white appearance produced by a broadband D65 source. In this study, we carried out an experiment to test a hypothesis that the neutral white appearance can be produced by a broadband stimulus with a CCT at 6500 K.

We used a spectrally tunable LED device to produce various sources to simulate the standard CIE daylight illuminants between 5000 and 10000 K. The observers switched among the sources and selected the one produce the natural white appearance. Then the observer performed a color matching task to match the color appearance of an LCD display to the selected neutral white produced by the source. It was found that on average, the sources selected by the observers to have the neutral white appearance had a CCT around 6500 K, and the displays were adjusted to have a CCT higher than 6500 K to match the color appearance of the selected neutral white.

The results clearly supported our hypothesis, and further suggested the importance of considering display spectral compositions in color specification, and the necessity to have a new set of CMFs for color specification and calibration.

References

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Author Biography

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