Whiteness Boundary for Surface Colors

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Abstract

A psychophysical experiment was conducted to investigate the whiteness boundary for surface colors. Forty-four color normal observers evaluated the whiteness appearance of 88 color samples using a forced-choice and a magnitude of estimation method under four lighting conditions (i.e., 3000, 4000, 5000, and 6500K) whose spectral power distributions were carefully designed to have strong violet radiation, create obvious blue appearances for the samples with FWAs. The data collected was combined with those from the two recent studies to fit ellipoides in color spaces to define the whiteness boundary for each CCT levels. It was found that the whiteness boundaries are different for different CCT levels. Samples that have a hue of blue and high chroma simultaneously were still judged as white under the 3000K illumination.

Introduction

White is an important color for surface colors, as there are numerous number of objects around us, including man-made or natural objects, have a white appearance. Many of these white objects contain different amounts of the fluorescent whitening agents (FWAs), which are added to enhance the whiteness appearance. FWAs absorb the ultraviolet or violet radiations that incident on the surfaces and re-emit the blue light radiation through the fluorescence effect, which can increase the lightness and introduce a blue tint. The combined effect of blue tint and lightness increase results in a whiteness enhancement.

Efforts have been made to investigate how to characterize the whiteness appearance of a surface color, especially for those contain FWAs. The most widely used measure is the CIE whiteness formula [1], which characterizes the appearance of a sample with a whiteness value W_{CIE} and a tint value T_{CIE}:

$$W_{CIE} = Y + 800(x_n - x) + 1700(y_n - y) \tag{1}$$

$$T_{CIE} = 900(x_n - x) - 650(y_n - y) \tag{2}$$

where Y and x,y are the Y tristimulus value and the chromaticity coordinates of a sample illuminated by CIE standard D65 illuminant; x_n,y_n are the chromaticity coordinates of a perfect reflector under D65 illumination. All the values are calculated using the CIE 1964 10° Standard Observers. Both formulas, however, can only be used for the samples whose whiteness and tint values are inside the boundary defined by:

$$40 < W_{CIE} < 5Y - 280 \tag{3}$$

$$-4 < T_{CIE} < +2 \tag{4}$$

The shortcomings of the CIE whiteness formula have been well documented. For example, it cannot characterize the whiteness appearance of a sample under a non-D65 illuminant and does not consider the effect of spectral power distribution (SPD) of an illumination on the whiteness appearance of a sample. And the boundary defined by Equations (3) and (4) has been found too small [2]. With these in mind, a new technical committee, CIE TC1-95 *The Validity of the CIE Whiteness and Tint Equations*, was established in 2015, with the goals to accumulate new experimental data, to make modifications on the CIE whiteness and tint equations, and to update the whiteness boundary.

This paper describes a study that was purposely designed to investigate the whiteness boundary for surface colors along the blue/yellow direction. A 14-channel spectrally tunable LED device was used to generate lighting spectra with strong violet radiation, which was never realized and studied before. Together with the two recent studies [3,4], a new whiteness boundary is proposed.

Methods

Apparatus, Lighting Conditions, and Samples

A 14-channel spectrally-tunable LED lighting system (i.e., *LEDCube*) was used to produce the desired lighting conditions. The 14 channels included in LEDCube had peak wavelengths between 350 and 700 nm, whose intensities can be adjusted wirelessly through a computer program. LEDCube was placed above a viewing booth, whose dimensions were 50 cm (width) x 50 cm (length) x 60 cm (height) and interiors were painted using Munsell N7 paint, to provide a uniform illumination to the floor of the booth.

Four lighting conditions, with nominal CCTs at 3000, 4000, 5000, and 6500K, were created. Typically, the amount of ultraviolet/violet radiation of an illuminant is strictly controlled and characterized using some measures in surface color industry. For example, the quality of CIE daylight simulators in simulating D-illuminants is rated using the CIE metamerism index M_u and M_v. The four lighting conditions in this study, however, were purposely designed to have a strong radiation by increasing the intensities of the violet channels in the LEDCube to make some samples with FWAs have an obvious blue appearance, allowing us to define the boundary. The SPDs and the colorimetric characteristics of the four lighting conditions, as measured using a calibrated JETI specbos 1211™ spectroradiometer from 230 to 1000 nm and a reflectance standard at the center of the floor in the booth, are summarized in Figure 1 and Table 1. The luminance at the center of the floor was calibrated at about 160 cd/m^2.

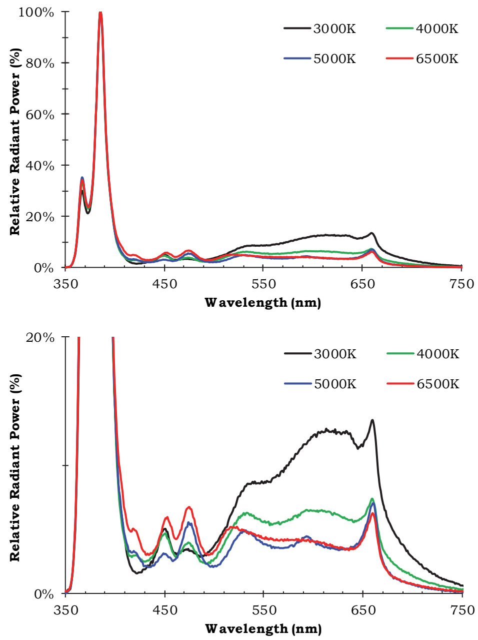

Figure 1 The relative spectral power distribution of the four lighting conditions.

Table 1 Colorimetric characteristics of the lighting conditions

Nominal CCT	CCT	D_{uv}	R_a	L (cd/m^2)	M_v	M_u
3000K	2991	+0.0001	90.6	161.4	-	-
4000K	4001	+0.0003	91.3	161.5	-	-
5000K	4992	+0.0004	95.8	162.2	0.89	53.8
6500K	6467	-0.0004	96.5	164.2	0.53	37.6

Eighty-eight color samples, including 45 NCS and Pantone matte samples, 28 fabric samples, 10 paper samples, and 5 plastic samples, were carefully selected from a large number of samples, including NCS samples, Pantone color samples, fabric samples, plastic samples, and paper samples, under the 6500 K lighting condition, with a goal to make them widely distributed along the yellow/blue direction in a color space at different lightness levels, as illustrated in Figure 2.

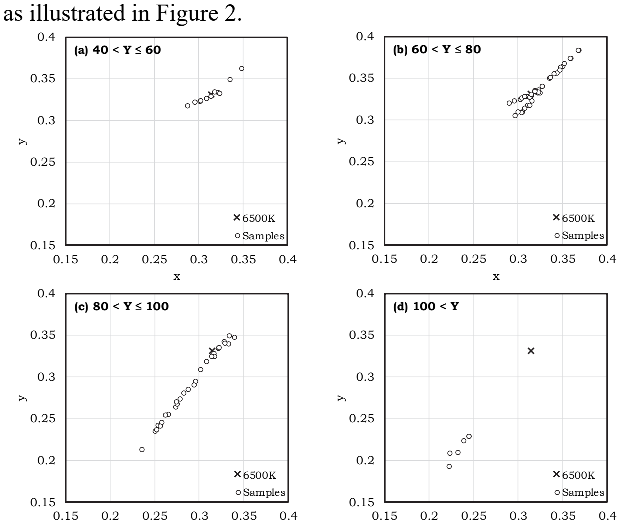

Figure 2 Chromaticity distribution of the 88 samples under the 6500K lighting condition at different luminance factor levels, calculated using the CIE 1964 Color Matching Functions (CMFs).

Observers and Visual Evaluations

Forty-four naïve observers (14 females and 30 males) between 21 and 26 years of age (mean = 21.6, std. dev. = 1.25), participated in the experiment. Most observers made evaluations under two different lighting conditions and some only made evaluations under a single lighting condition. In total, 20 observers made evaluations under each lighting condition.

During the experiment, each observer was asked to keep his/her chin and forehead on a chin-and-forehead rest, so that observers perceived the samples at an illumination and viewing geometry of 0°:45°. At the beginning of each session, each observer was asked to look into the viewing booth under illumination for three minutes, which allowed him/her to chromatically adapted to the lighting condition. Then, each sample was placed by the experimenter at the center of the floor, he/she was asked to observe the sample and to give two judgments—a forced choice and a magnitude estimation. Each observer was asked to judge whether the color of the sample can be regarded as white (i.e., either "yes" or "no") and what is the whiteness percentage of the sample (i.e., 100% means a pure white and 0% means no trace of white). The samples were presented in a random order. It took around 30 minutes to evaluate all the 88 samples under each lighting condition.

Results and Discussions

Inter-observer Variation and correlation between two judgments

The inter-observer variations were characterized using *STRESS* values by comparing the whiteness percentage value of each sample rated by each observer and that of each sample rated by an average observer, which is the mean whiteness percentage value of each sample. The mean *STRESS* values for the 20 observers were 39.7, 35.5, 31.3, and 31.8 for 3000, 4000, 5000, and 6500K lighting conditions respectively, which are generally comparable compared to past studies. The 3000K lighting condition, however, produced largest inter-observer variation.

The two evaluations made by the observers were positively correlated to each other. A higher percentage of the votes for samples that can be considered as white corresponds to a higher whiteness percentage value, as shown in Figure 3. It can be found that the 50% of the votes corresponds to a whiteness percentage value of 56%, which was a little different from the recent two studies (it was found to be 70% before). This could be due to the fact that the observers included in this current study were all naïve observers.

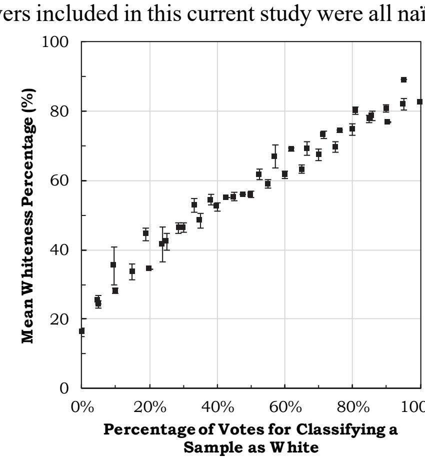

Figure 3 The relationship between the two judgements made by the observers.

Whiteness Boundary for Surface Colors

The data collected from the current experiment were combined with the data collected from the two recent experiments, both of which were also designed to investigate the whiteness appearance of different lighting conditions.

Evaluation of CIE whiteness limit

As specified in Equations (3) and (4), the CIE whiteness formula only allows the characterization of whiteness appearance when the chromaticity of a sample is within a certain range under a 6500K illumination. It was found that 241 of the 348 samples had a consistent classification between visual evaluation and using the CIE whiteness limit, with 76 being classified as non-white and the other 165 being classified as white. All the other 107 samples were outside the CIE whiteness limit, but they were all evaluated as white by the observers.

As shown in Figure 4 (b) and (c), the CIE whiteness formula requires samples to have low chroma, and the chroma tolerance for samples with a hue angle around 270° is slightly higher. Visual assessments, however, allowed samples with higher chroma level to be classified as white, especially for those with a hue angle around 270°.

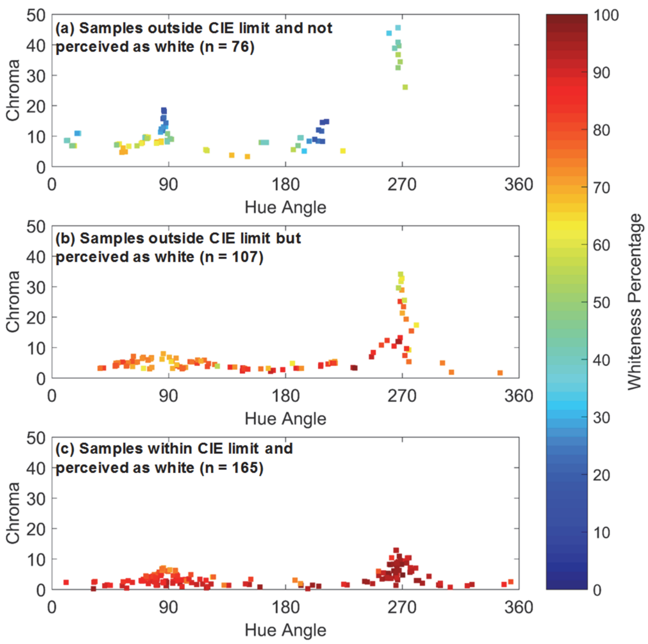

Figure 4 Chroma versus hue angle of the samples under the 6500K lighting condition calculated using CAM02-UCS, color coded with the average whiteness percentage values evaluated by the observers.

Whiteness boundary in xyY space

Figures 5a and 5b show the distribution of the samples under each lighting condition calculated using the CIE 1964 Standard Colorimetric Observer in *xy* and *xY* planes, respectively.

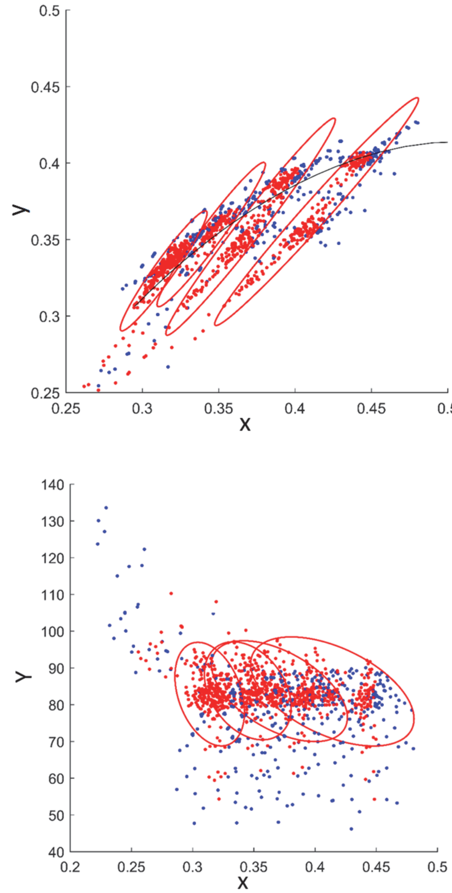

Figure 5 The chromaticity coordinates and fitted ellipsoids of whiteness boundary for different CCT levels in xyY color space.

The ellipsoids were fitted based on the chromaticity coordinates of the samples whose colors were judged as white. It can be observed that the shape of the ellipsoids is different for different CCT levels, with a higher eccentricity value for a lower CCT level. Such a discrepancy between different CCTs could be due to the characteristics of non-uniformity and no capability of chromatic adaptation in *xyY* color space. It can be seen that all 4 ellipses in *xy* plane were long and thin and had about the same angle orientation in the yellow/blue direction. Also, the ellipses for the higher CCTs were larger than those of lower CCTs.

Whiteness boundary in CAM02-UCS

The chromaticity coordinates of each sample under each lighting condition were calculated in CAM02-UCS, which is a quite uniform color space and includes CAT02 for considering the effect of chromatic adaptation on color appearance for surface colors. Full complete chromatic adaptation was assumed in the calculation, given the high luminance level and the adaptation time used in the experiment [5]. Figures 6, 7, and 8 show the chromaticity distribution and the fitted ellipsoids in three different planes in CAM02-UCS.

It can be observed from Figure 4 that the ellipsoids are similar for different CCTs in *a'-J'* plane. However, they were quite long and thin in *b'-J'* plane.

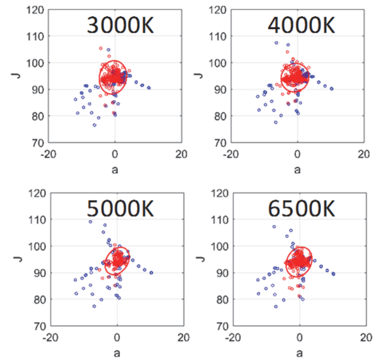

Figure 6 The chromaticity coordinates and fitted ellipsoids of whiteness boundary for different CCT levels in a'-J' plane of CAM02-UCS.

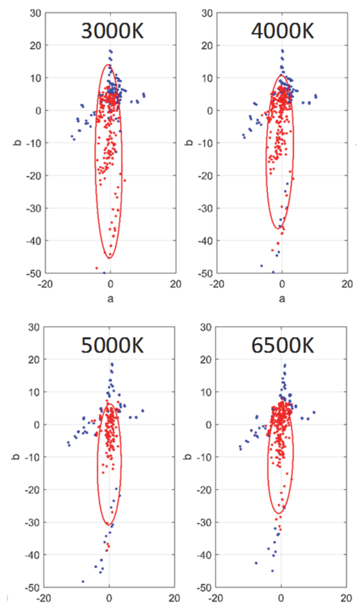

Figure 7 The chromaticity coordinates and fitted ellipsoids of whiteness boundary for different CCT levels in a'-b' plane of CAM02-UCS.

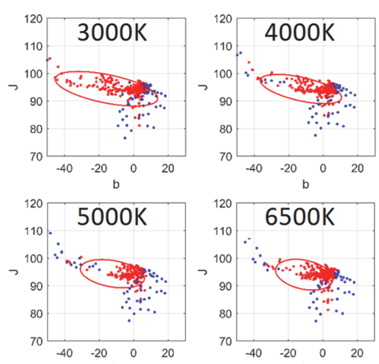

Figure 8 The chromaticity coordinates and fitted ellipsoids of whiteness boundary for different CCT levels in b'-J' plane of CAM02-UCS.

However, the blue shift introduced by the interaction of FWAs and the ultraviolet/violet radiation included in the illuminations caused difference in whiteness appearance, as shown in Figures 7 and 8. It can be observed that under lower CCT levels, samples with a high chroma value and blue hue were still perceived as white, which could be due to the incomplete chromatic adaptation under the low CCT levels as identified in recent studies [4,6]. This could also be caused by the unusual UV content included in 3000K lighting condition (see the SPD of 3000K in Figure 1). The intension to have strong UV was to reveal maximum white appearance in the illumination studied. The lengths of the semi-long- and semi-short-axis and the center of the ellipses in a'-b' plane are summarized in Table 2. It can be seen that all ellipses are pointed in the yellow blue direction with a hue angle about 180°. The lower CCT ellipses are large and thin comparing with higher CCT ones.

Table 2 Summary of the ellipses in Figure 5

CCT	Long - Axis (A)	Short-Axis (B)	Ratio (A/B)	Orien tation	a'	b'	Area
3000	29.7	4.1	7.2	181.0	-0.6	-5.7	19.6
4000	23.5	4.2	5.7	177.3	-0.7	-2.8	17.6
5000	18.6	3.6	5.1	178.6	0.0	-2.3	14.5
6500	16.6	3.8	4.3	176.1	-0.2	-0.7	14.1

Conclusion

Psychophysical experiments were conducted to investigate the whiteness boundary for surface colors under different CCT levels. Observers evaluated 88 samples under each lighting condition, and judged whether the color of the sample can be regarded as white and the whiteness percentage of the sample. Data collected was combined with the two other recent experiments. Ellipsoids were fitted in xyY and CAM02-UCS color spaces to define the whiteness boundaries, which were found different for different CCT levels. For lower CCT levels, samples with a blue hue and high chroma value were still perceived as white, which could be due to the incomplete chromatic adaptation under the low CCT levels.

For the samples within the whiteness boundary defined in this study, a comprehensive whiteness formula is under development to characterize the whiteness appearance of surface colors under an arbitrary illuminant, which will make important contribution to the surface color industry for surface color appearance characterization and LED lighting industry for developing high quality LED lighting.

Acknowledgement

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