Impact of spectral power distribution of daylight simulators on whiteness specification for surface colors

Minchen Wei* and Siyuan Chen

Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong
**minchen.wei@polyu.edu.hk*

Abstract: The impact of spectral power distribution of daylight simulators (i.e., D65 simulators) on surface whiteness specification was investigated by focusing on how CIE whiteness and tint values of eight whiteness samples with fluorescent whitening agents (FWAs) vary under different D65 simulators. Large variations in both whiteness (~16 points) and tint (~1.6 points) are observed under the D65 simulators above BB grade, as characterized using the CIE Metamerism Index. However, it is found the variations of the whiteness and tint values are smaller under the D65 simulators whose radiant power in the UVA band (i.e., 300-340 nm) was within ±30% in comparison to CIE standard D65 illuminant, as defined in BS 950, which may be a better alternative for evaluating the quality of a D65 simulator for surface white specification using CIE whiteness and tint formulas. The findings also suggest the necessity to fine-tune or revise the CIE whiteness and tint formulas to characterize the surface whiteness under non-perfect D65 simulators or arbitrary light sources.

Keywords: Daylight simulator, Whiteness Specification, Surface Colors, Metamerism Index

1. Introduction

1.1 Daylight simulator

Standard illuminants, including daylight illuminants, are theoretical models whose spectral power distributions (SPD) are specified and defined by the *International Commission on Illumination (CIE)* [1]. The daylight illuminants, however, cannot be precisely realized in practice for colorimetric and photometric measurement or calibration. Artificial sources are then developed to simulate these standard daylight illuminants, which are called *daylight simulators*. Daylight simulators, especially D65, are important and widely used in color and imaging applications (e.g., surface color characterization, camera white balance calibration, and CCD sensor calibration). They use various electric light sources, including high-pressure short-arc xenon lamps with or without filters, filtered tungsten-halogen, tungsten-iodine lamps, and fluorescent lamps, to simulate the SPDs of the standard daylight illuminants [2]. With the development of LEDs, the quality of LED-based daylight simulators is becoming better and better [3].

Two methods have been proposed to evaluate the quality of a daylight simulator in simulating a standard daylight illuminant, either by comparing the SPDs directly or by comparing the appearance of a color sample set. The former includes the goodness of fit method [2] and the band value method [4]; the latter includes the CIE Metamerism Index method [5]. In color and imaging industry, the CIE Metamerism Index is the most widely used method, which was initially proposed in 1981 and was adopted by an ISO/CIE standard in 2004 [5].

The CIE Metamerism Index includes two values, with one for the visible range (i.e., M_v) and one for the ultraviolet range (i.e., M_u). M_v is the average color difference of the five virtual metameric pairs of color samples illuminated by a simulator; M_u is the average color difference of the three pairs of virtual fluorescent color samples illuminated by a simulator. The color differences are characterized in the CIELAB color space using the CIE 1964 Color Matching Functions (CMFs). Based on M_v and M_u values, the quality of D50, D55, D65, and D75 daylight simulators can be graded according to the criteria listed in Table I, if the chromaticity difference between a simulator and the corresponding CIE standard daylight illuminant is less than 0.015 in CIE 1976 UCS using the CIE 1964 CMFs. The quality of a daylight simulator is then reported using two letters, with the former representing the visible range and the latter representing the ultraviolet range. For example, a daylight simulator with a BA grade means grade B for the visible range and grade A for the ultraviolet range.

Table I Quality grade of daylight simulators D50, D55, D65, and D75 standardized in ISO 23603/CIE S012 [5]

Quality Grade	CIE Metamerism Index M_v or M_u
A	≤ 0.25
B	0.25 to 0.50
C	0.50 to 1.00
D	1.00 to 2.00
E	> 2.00

1.2 Colorimetric specification for surface colors

The colorimetric characteristics of surface colors are commonly specified under standard illuminants in surface color industry. For example, the hue, value, and chroma of the Munsell samples are specified under CIE illuminant C and the Natural Color System (NCS) notations for the NCS samples are specified under CIE illuminant D65 [6]. Thus, daylight simulators play an important role in color specification for surface colors.

In addition to the familiar specification we use for surface colors, whiteness is also an important colorimetric characteristic, especially for the whites containing fluorescent whitening. FWAs are added to most man-made white objects for whiteness enhancement, as whiteness appearance is always associated with cleanness, freshness, freedom from contaminants, and good quality. FWAs absorb the violet and ultraviolet radiation from the illumination and re-emit blue light, which induces a blue tint and increases the lightness [7]. The induced blue tint aims to neutralize the yellow tint of the materials of natural and man-made objects, such as cotton fibers and wood-pulps, and the increased lightness aims to make the objects appear brighter.

Various whiteness formulas have been proposed since 1934 [8]. Some characterize the whiteness of a surface based on the chromaticity distance between the surface and a perfect diffuser (i.e., a Magnesium Oxide plate) under CIE Illuminant C in a color space. Thus, any departure from a perfect diffuser is regarded as a decrease in whiteness [9-11], which does not consider the effect of FWAs and is mainly for samples with a dominant wavelength around 575 nm. The formula proposed by Ganz, known as "Ganz formula" (Equation 1) was the first one to consider the samples with a dominant wavelength around 470 nm due to the effect of FWAs.

$$W = D \cdot Y + P \cdot x + Q \cdot y + C \tag{1}$$

where Y, x, y are the lightness and the chromaticity coordinates of a sample; D, P, Q, and C are the coefficients to determine the "whiteness bias" [12].

In 1986, CIE recommended a whiteness formula, Equation 2 [1], based on Ganz formulas [13].

$$W = Y + 800(x_n - x) + 1700(y_n - y) \tag{2}$$

where Y, x, y are the lightness and the chromaticity coordinates of a sample under CIE standard illuminant D65; x_n,y_n are the chromaticity coordinates of CIE standard illuminant D65. The chromaticity coordinates can be calculated using either the CIE 1931 CMFs or the CIE 1964 CMFs.

In addition, two tint formulas, Equations 3 and 4, were proposed, as Ganz noted that a single whiteness value cannot completely characterize the whiteness appearance for surface colors [13], with Eq 3 using the CIE 1931 CMFs and Eq 4 using the CIE 1964 CMFs.

$$T = 1000(x_n - x) - 650(y_n - y) \tag{3}$$

$$T_{10} = 900(x_n - x) - 650(y_n - y) \tag{4}$$

It is further noted that the CIE whiteness formula and the tint formulas can only be used when $40 < W < 5Y-280$ and $-4 < T$ (or T_{10}) $< +2$ [1].

Though the limitations of the CIE whiteness formulas have been documented and efforts have been made to improve the performance of the CIE whiteness formulas (e.g., Uchida extended the range of the CIE whiteness formula in 1998 [14]), it is still the most widely used metric to characterize the whiteness appearance of surface colors and is adopted in the standard issued by the International Organization for Standardization (ISO) [1]. The chromaticity coordinates, together with the CIE whiteness and tint values, of a sample reported in a specification are actually measured and calculated under an artificial D65 simulator, which are actually affected by the quality of the D65 simulator. In this paper, we investigate the impact of SPD of D65 simulators on whiteness specification for surface colors, based on the colorimetric measurements and computations.

2. Whiteness samples and D65 simulators investigated

2.1 Whiteness samples

Eight whiteness samples with different amounts of FWAs (denoted as S1 to S8) were included in the investigation, which represent typical paper, plastic, and textiles around us. The samples had CIE whiteness values between 102.8 and 158.8, and CIE tint values between +0.11 and 3.72 under CIE standard D65. The Donaldson matrix of each sample was measured using the double-monochromator method [15], with a wavelength range between 300 and 780 nm. The diagonal of a Donaldson matrix represents the spectral reflectance of a sample; the off-diagonal elements represent the fluorescence effect of a sample.

2.2 D65 simulators

Three sets of D65 simulators were included in the analyses. 1) Physical D65 simulators using conventional light sources. These D65 simulators use conventional light sources, such as xenon lamps, fluorescent lamps, incandescent lamps, or dichroic lamps. Some SPDs are documented in [16]; the others were measured using a calibrated spectroradiometer JETI Specbos 1211UV. 2) Physical D65 simulators produced using a spectrally-tunable LED device. A spectrally-tunable LED device that has 14 channels with a peak wavelength between 350 and 700 nm, was used to produce the lighting conditions in a viewing booth. The SPDs were measured using a calibrated spectroradiometer JETI Specbos 1211UV. 3) Synthetic D65 simulators through computer simulation. These D65 simulators contained multiple synthetic LED channels (n=5, 6, and 7). The SPD of each channel was approximated and simulated using a Gaussian distribution with a peak wavelength λ_i (i=1,2…n) and a full width at half maximum (FWHM) of 30 nm, a typical value for AlInGaP and AlGaInN LEDs [17]. To achieve the target chromaticities of CIE standard D65 using the CIE 1964 CMFs, the intensities of the two channels, I_n and I_{n-1}, can be calculated based on the peak wavelengths $\{\lambda_1, \lambda_2 \ldots \lambda_n\}$ and the intensities of the other channels $\{I_1, I_2 \ldots I_{n-2}\}$ based on the color-mixing constraints. Thus, $\{I_{n-1}, I_n\} = f(\lambda_1, \lambda_2 \ldots \lambda_n, I_1, I_2 \ldots I_{n-2})$. With a goal to optimize the performance of the simulators, a genetic algorithm was used to minimize the objective function—Equation 5. The optimization to minimize Equation 5 was conducted by running λ_1 from 300 to 400 nm, with a 1 nm step, which was needed to render the three pairs of the fluorescent samples for calculating M_u. For each λ_1, $\{\lambda_2 \ldots \lambda_n\}$ was constrained within $\lambda_i \in [\lambda_1, 780]$ and $\{I_1 \ldots I_{n-2}\}$ was constrained within $I_i \in [0,1]$.

$$F(\lambda_1, \lambda_2 \ldots \lambda_n, I_1, I_2 \ldots I_{n-2}) = M_v + M_u \tag{5}$$

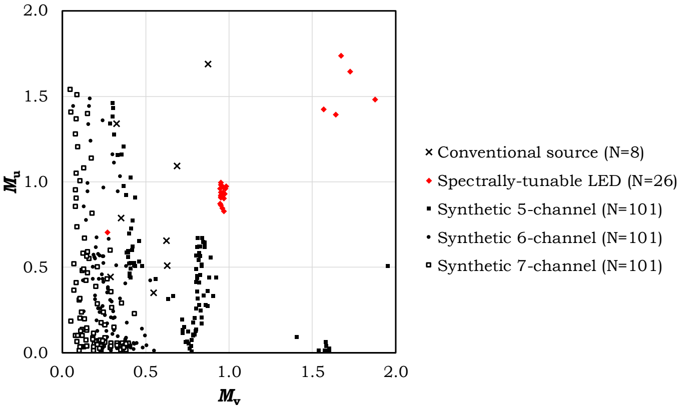

Figure 1 Scatter plot of M_u versus M_v for the 337 D65 simulators.

In total, there were 337 simulators, which had SPD data between 300 and 780 nm with a 5-nm interval, without interpolation or extrapolation. Both M_u and M_v were calculated for these 337 SPDs, as shown in Figure 1. Only 151 SPDs, which had both M_u and M_v values below 0.50 (i.e., above grade B for both visible and ultraviolet ranges) were retained for analyses; 148 of these 151 SPDs had a CIE General Color Rendering Index (CRI R_a) above 95. CIE standard D65 illuminant, whose SPD is documented in [1], was used as a reference.

Among these 151 simulators, 69 had a quality grade of A for the visible range and 113 had a grade A for the ultraviolet range. The average M_v and M_u for these 151 simulators were 0.27 and 0.16 respectively.

3. CIE whiteness values and tint values

The CIE whiteness value (W) and tint value (T) of each sample were calculated under each simulators and CIE standard D65, using Equations 2 and 4. Figure 2 is the scatter plot of T versus W for each sample.

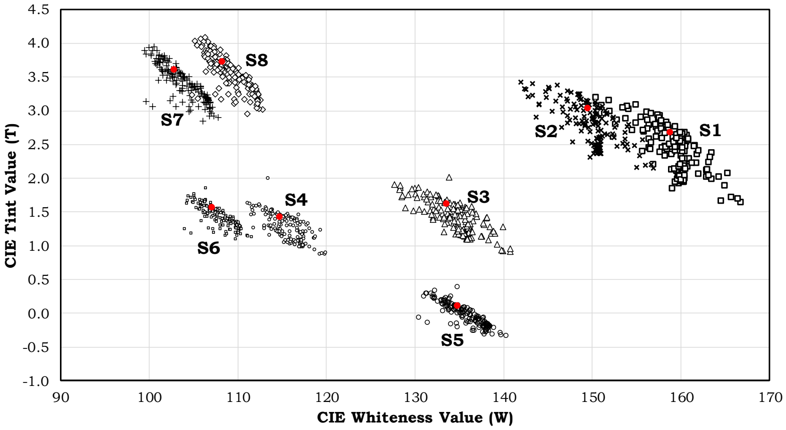

Figure 2 Scatter plot of the CIE tint value (T) versus the CIE whiteness value (W) of each sample (S1-S8) under each D65 simulator. The red dot represents the sample under CIE standard D65 whose SPD is documented in [1].

Large variations can be observed in both W and T values, especially for the samples with higher amount of FWAs (i.e., S1 and S2), though all the 151 simulators were above BB grade. As shown in Figure 3, a whiteness sample can have 16-point difference in the CIE whiteness value and 1.6-point difference in the CIE tint value. More importantly, such a variation disqualifies the CIE whiteness formula for some samples, as the tint value is outside the boundary.

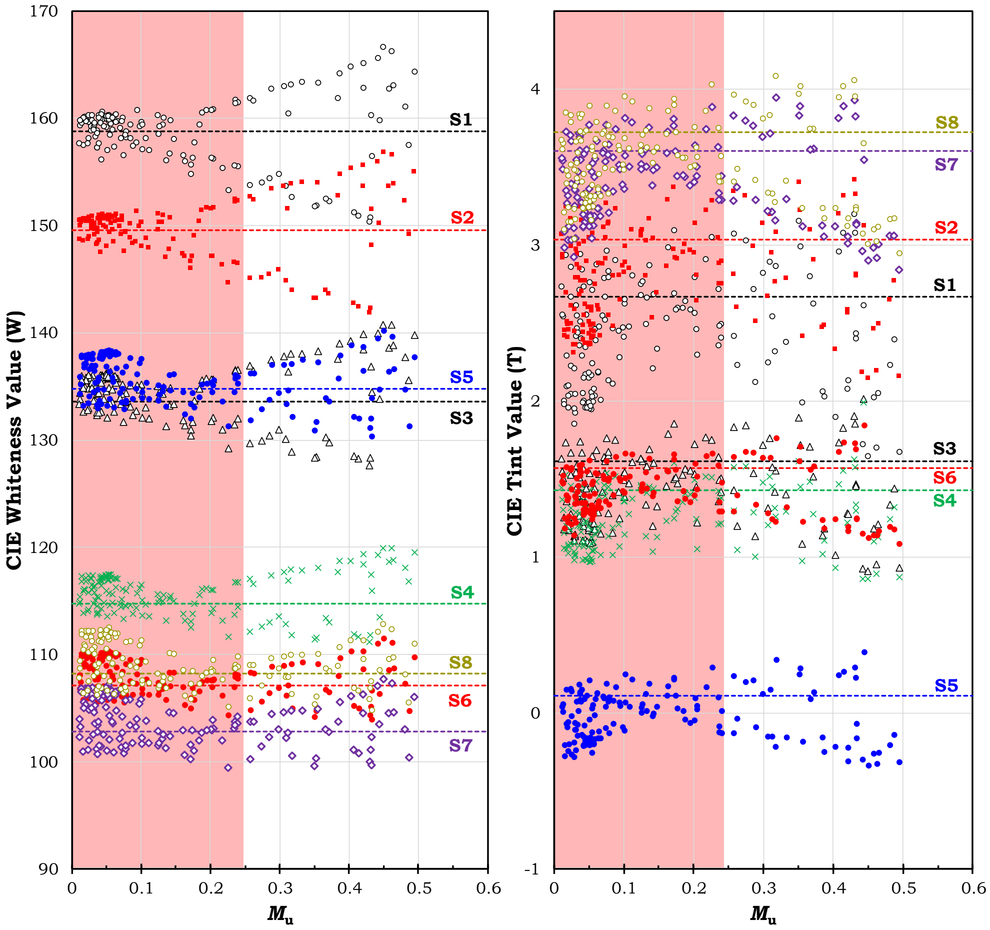

Figure 3 Scatter plot of the CIE whiteness value (W) and the CIE tint value (T) of each sample (S1-S8) under each D65 simulator versus the CIE ultraviolet-range metamerism index (Mu). The dotted line represents the CIE whiteness and tint values of each sample under CIE standard D65 whose SPD is documented in [1]. The red region represents the daylight simulators whose Mu value was smaller than 0.25 and could be graded as grade A for the ultraviolet range. Left: CIE whiteness value; Right: CIE tint value.

Furthermore, it can be observed that simulators with higher M_u values cause larger variations in the whiteness value. However, even for the simulators with an A-grade for the ultraviolet range (i.e., $M_u <= 0.25$), the whiteness value can still vary as large as 10 points. On the contrary, the relationship between M_u and the variation of the tint value T is less obvious.

4. Chromaticity shifts of the color samples

To further investigate the impact of the SPD of the simulators, the chromaticity coordinates of each sample under each simulator and under CIE standard D65 illuminant were calculated in CIE 1976 UCS using the CIE 1964 CMFs. The Euclidian distance [1,2] was then calculated as the chromaticity shift, as shown in Figure 4. For comparison, the chromaticity shifts were also calculated for the 99 Color Evaluation Samples (CES) included in the IES TM-30-15 [18], which were carefully selected from more than 105,000 real objects with a good color space and wavelength uniformity. These 99 samples do not contain any FWAs.

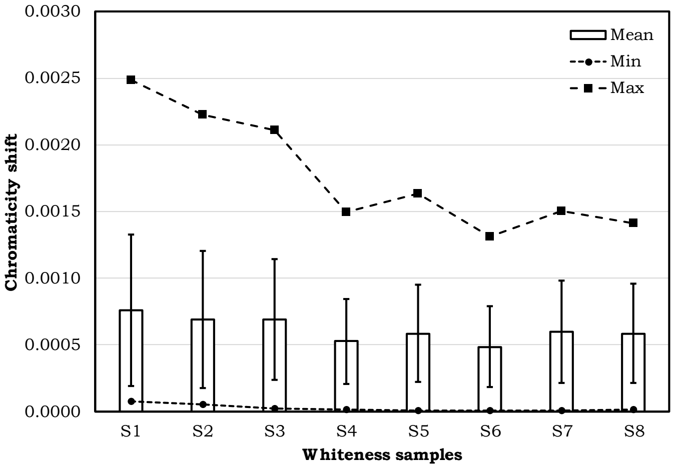

Figure 4 The average (together with the standard deviation bar), minimum, and maximum of the chromaticity shifts of each sample under the 151 D65 simulators in CIE 1976 UCS using the CIE 1964 CMFs.

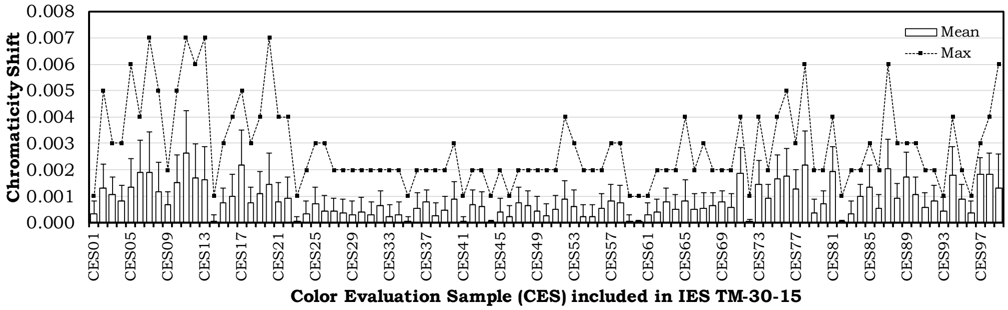

Figure 5 The average (together with the standard deviation bar) and maximum of the chromaticity shifts of each Color Evaluation Sample (CES) included in IES TM-30-15 [18] under the 151 D65 simulators in CIE 1976 UCS using the CIE 1964 CMFs (note: the minimum chromaticity shift is not shown, as all of them are zero).

Figures 4 and 5 show the average, the maximum, and the minimum chromaticity shift of the eight whiteness samples and the 99 CES under these 151 simulators respectively (note: the minimum chromaticity shift for each of the 99 CES is not shown in Figure 5, as all of them are zero). It can be observed that the magnitude of chromaticity shifts of the eight whiteness samples and the 99 CES under these 151 simulators from CIE standard D65 were similar, with an average value of 6.1×10^{-4} for the eight whiteness samples and 8.2×10^{-4} for the 99 CES.

5. Discussions and conclusion

Though the 151 D65 simulators retained for analyses were all above BB grade as characterized using the CIE Metamerism Index, the eight samples had large variations in CIE whiteness and tint values under these simulators, even for those with an A-grade for the ultraviolet range, as shown in Figure 3. Such a difference is likely to be perceptible to human eyes based on the findings of the recent psychophysical experiments [19-21] and may also disqualify the use of the CIE whiteness and tint formulas. Coupled with the increasing popularity of the LED-based daylight simulators [3,22], the large variations revealed here raise the question about whether the CIE Metamerism Index should be used to evaluate the quality of a D65 simulator for surface whiteness specification using the CIE whiteness and tint formulas.

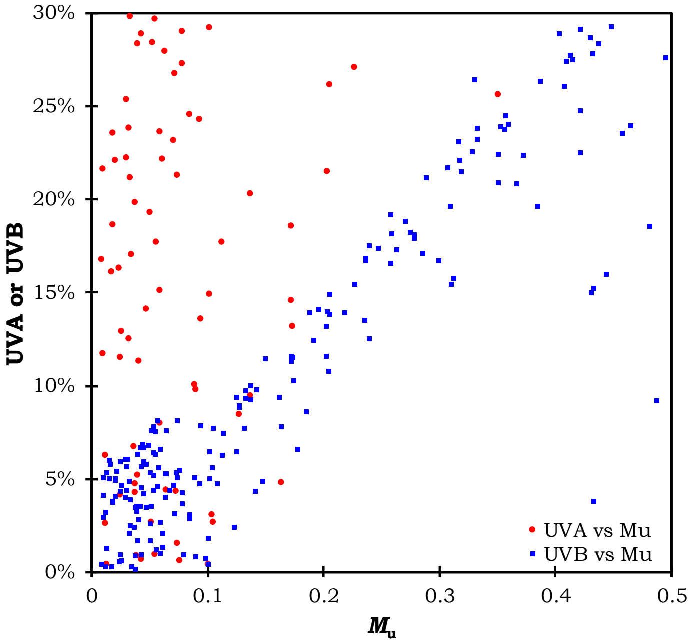

Figure 6 Scatter plot of UVA and M_u values for each source (red dots) and UVB and M_u values for each source (blue squares). Only the sources whose M_u value are smaller than 0.5 (i.e., above B grade for ultraviolet range), UVA and UVB values are smaller than 30% are shown here.

Besides the CIE Metamerism Index, the quality of a D65 simulator can also be evaluated using the band value method, as specified in BS 950-1:1967 [4]. It separates an SPD into eight bands, with two in the ultraviolet range (i.e., 300-340 nm for UVA band and 340-400 nm for UVB band) and the other six in the visible range from 400-760 nm. It requires the radiant power in both UVA and UVB bands of a D65 simulator to be within ±30%, in comparison to CIE standard D65. In addition, the luminous flux of a D65 simulator in each of the six bands in the visible range is also required to be within ±15%, in comparison to CIE standard D65. As the radiations in the ultraviolet and violet range are critical to excite the FWAs, the scatter plot between UVA and M_u and between UVB and M_u for sources that are above B-grade for M_u are shown in Figure 6. In total, 74 simulators are within ±30% in the UVA band and 199 simualtors are within ±30% in the UVB band. It can be observed that for sources above a B-grade for the ultraviolet range, M_u has a higher correlation to UVB than to UVA, which is likely due to the high spectral external radiant efficiency values between 340 and 400 nm for two of the three fluorescent samples used in M_u calculation [5].

Smaller variations in CIE whiteness and tint values can be observed for the eight whiteness samples under the simulators whose radiant power is within ±30% in the UVA band, as shown in Figure 7. The comparison between Figure 3 and 7 suggests that the quality of a D65 simulator for surface whiteness specification using the CIE whiteness and tint formulas may be better evaluated based on its radiant power in the UVA band, in comparison to the CIE Metamerism Index.

Figure 7 Scatter plot of the CIE whiteness value (W) and the CIE tint value (T) of each sample (S1-S8) under each of the 337 D65 simulator versus the difference of radiant power within UVA band (i.e., 300-340 nm) of each simulator in comparison to that of CIE standard D65 [3]. The dotted line represents the CIE whiteness and tint values of each sample under CIE standard D65 whose SPD is documented in [1]. The red region represents the difference in UVA band is within ±30%, which is included in [3] as a criterion for high quality D65 simulator. Left: CIE whiteness value; Right: CIE tint value.

Furthermore, the results presented here also indicate the great impact of spectral power distribution of an illuminant on surface whiteness, which has also been suggested by several recent psychophysical experiments [23-25]. For illuminants that cannot simulate CIE standard D65 with a high quality, the CIE whiteness and tint formulas should not be used. Because of the large differences encountered in the case of less than perfect D65 illumination, it is recommended to revise the limits set by the ISO 23603/CIE S012 and the BS 950 standards. It is also necessary to fine-tune the coefficients in the CIE whiteness and tint formulas for non-perfect D65 simulators and any other light source. The full revision of the formulae may also be necessary.

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Author Biographic Information

Dr. Minchen Wei is an Assistant Professor at the Department of Building Services Engineering, The Hong Kong Polytechnic University. He earned his BEng in Illuminating Engineering & Light Sources from Fudan University (China) in 2009, MSc and PhD in Architectural Engineering from The Pennsylvania State University (USA) in 2011 and 2015. Siyuan Chen is a PhD student at the Department of Building Services Engineering, The Hong Kong Polytechnic University. He earned his BEng from Tongji University (China) in 2016.