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Extension of CIE Whiteness Metric under different illuminants

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Abstract

An experiment was conducted to extend the CIE whiteness metric under white sources having different CCTs. Three versions based on CIE whiteness index were derived and they all gave similar degree of accuracy in predicting experimental data. The one with CAT02 performed quite well and is simple to use by applying the original CIE whiteness index under D65. The tint limits were also verified and a limit of ±5T is proposed.

INTRODUCTION

Whiteness is an important quality parameter in the surface colour industries, e.g. paper substrates, textile materials such as wool, cotton, detergents or washing power determines the value of a product. In general, a whiter material, the more expensive will be. Optical Brightening Agents (OBAs), also called Fluorescent Whitening Agents (FWAs), have been widely used in these manufacturing industries as part of the chemical process to achieve the required bluish-white brightness that consumers have grown to expect of white products. OBAs have the ability to absorb ultraviolet (UV) light and re-emit light at a usually longer wavelength and often in the purple or blue region of the spectrum, i.e. an increase in perceived whiteness with the help on a chromatic shift towards the blue [1].

Whiteness metrics have been developed over the years. The Ganz-Griesser whiteness metric (see Equation (1)) was first proposed by Ciba-Geigy in 1971 [2].

$$W = (DY) + (Px) + (Qy) + C \qquad (1)$$

where Y is the Y tristimulus value and x, y are the chromaticity coordinates of the sample, and D, P, Q and C are coefficients whose magnitude determines the "whiteness bias" of the formula. These parameters are determined by a calibration method for a particular spectrophotometer. Calibration standards, such as the textile samples from the Hohenstein, and the AATCC (The American Association of Textile Chemists and Colourists), are required to obtain the coefficients in Equation (1).

In 1986, a formula [3] was recommended by the CIE and is denoted as W_{CIE}. This has been the most widely used whiteness index and it is defined by the formula given in Equation (2).This is a special version of the Ganz-Griesser whiteness formula [1] and is only defined for use with the D65/10° and D65/2° illuminant/observer combination.

$$W_{CIE} = Y + 800(x_n - x) + 1700(y_n - y) \qquad (2)$$

Where Y is the CIE1964 or 1931 Y tristimulus value and x, y and x_n, y_n are the chromaticity coordinates, in the CIE1964 or 1931 x, y chromaticity diagram, of the sample and the perfect diffuser illuminated by illuminant D65 respectively. The application of W_{CIE} is limited to the range $40 < W_{CIE} < (5Y - 280)$.

For the CIE whiteness index, there is a common restriction—T_w. The green/red tint value T_w can be calculated using Equations (3) and (4) corresponding to CIE 1964 10° Observer and 1931 2° Observer respectively:

$$T_{w,10} = 900(x_{n,10} - x_{10}) - 650(y_{n,10} - y_{10}) \qquad (3)$$

$$T_w = 1000(x_n - x) - 650(y_n - y) \qquad (4)$$

A sample assessed as greenish has a positive value of T_w whereas a sample assessed as reddish has a negative value: T_w is equal to zero if the tint does not significantly deviate from that of the white reference sample. For CIE 1964 10° Observer and CIE 1931 2° Observer, an object is white when the value of T_w lies within the range +2 to -4. So the application of CIE Whiteness is restricted to samples that can be called commercially 'white' [3].

The Uchida whiteness metric (W_{Uchida}) was published in 1998[4] and it is a modification to CIE whiteness index. The whiteness limits are extended such that the index calculated when $W_{CIE} > (5Y - 280)$. It also has the same T_w range as the CIE whiteness metric.

Some experiments were also conducted to test various whiteness metrics. Shendye et al. [7] found that the CIE whiteness metric had limitations when a sample had a high blue tone under both D65 and D50 sources and it could mislead manufacturers. Lin et al.[8] found that the CIE whiteness index gave higher correlation to visual assessments than the Uchida metric; the correlation was especially higher when the amount of UV content included in a source used for visual assessment was similar to that included in a source under which the radiance spectra of the samples were taken.

More recently, whiteness topic also gains interests from the LED lighting due to a shortage of UV composition in LED lights. David et al. [9] proposed a new metric of the CIE whiteness formulae to describe FWA-induced whiteness under any light source. Their results showed that violet-pumped LEDs can enhance the whiteness by tuning the amount of violet light without compromising the value of the colour rendering index (CRI). The most commonly used blue-pumped LEDs however, failed to excite the FWAs and showed no whiteness enhancement in the absence of a UV component. Furthermore, they also suggested that a reliable whiteness metric should be considered as a key colour quality metric for the rendering capability of a light source. The improvement of whiteness rendition without the cost of colour rendition quality was further validated in Wei et al. [10, 12].

With the above in mind, CIE TC1-95, the validity of the CIE Whiteness and Tint equation, was formed with an aim to accumulate new data to recommend modifications to the existing CIE whiteness and tint equations to extend their application to illuminants other than D65 and verify the limits defined by the tint equation. The current work closely follows the aims of this technical committee.

EXPERIMENTAL

For conducting the psychophysical experiment, a 14-channel LED lighting system was chosen to provide desired lighting. Fifty samples covering wide whiteness range were selected. And 8 observers with normal vision were recruited form Zhejiang University. They have an average age of 23.2 with a standard deviation of 1.5.

Lighting conditions and apparatus

A light booth coated with a mid-grey matte paint was used for visual assessment. The light settings were created using a 14-channel LED lighting system. Figure 1 shows 11 peak wavelength covered from 360 nm to 660 nm, in which two channels had their peak wavelength below 400 nm. The lighting system was controlled by software to produce the desired lighting quality.

In this experiment, 12 lighting conditions comprised 4 correlated colour temperature (CCT) levels (3000 K, 4000 K, 5000 K and 6500 K) with 3 UV levels (designated zero, medium and high) for each CCT value. One source (6500 K at high UV level) was repeated to examine the intra-observer variability. Lighting with CCT higher than 6500K was hardly used in industry.

Table 1 summarizes the measurement results of CIE 1964 xy chromaticity, UV levels, CCT, luminance, CIE general colour rendering index (CRI-R_{a}), distance from planckian locus (Du'v') and the Metamerism Index (MI) for 12 lighting conditions. Overall, the performance of the lighting conditions can be considered highly satisfactory for this study.

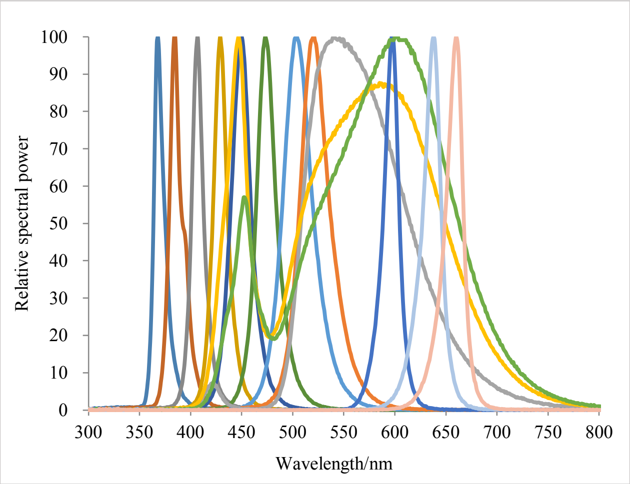

Figure 1. Relative SPD of 14 channels in the LED lighting system, normalized to peak power.

Fifty 'nominally white' samples were selected for the experiment: these included 38 textile and 12 paper samples. From the 38 textiles, they contained different amounts of FWA, resulting in different whiteness values. Figure 2 shows the chromatic distribution of all the samples plotted in CIE a*b* plane under D65/10°. It can be observed that some samples covered a relatively wide range of hues close to the neutral axis and some were distributed along a hue angle at approximately 290°.

Table 1. The parameters of the light sources [Note: for lighting conditions below 5000 K, no MI was defined in colorimetry]

	CCT	UV	*x*	*y*	L （cd/m²）	R_a	$D_{u'v'}$	MI-vis	MI-uv
1	3021	Zero(0)	0.434	0.400	388	98	0.0012	—	—
2	3095	Medium(25)	0.421	0.382	388	97	0.0071	—	—
3	3170	High(5)	0.409	0.364	389	95	0.0128	—	—
4	3997	Zero(0)	0.383	0.385	385	98	-0.0032	—	—
5	4143	Medium(25)	0.373	0.368	387	96	0.0021	—	—
6	4314	High(50)	0.364	0.352	388	94	0.0070	—	—
7	5022	Zero(0)	0.345	0.358	388	99	-0.0001	0.19	0.43
8	5027	Medium(25)	0.345	0.358	388	99	0.0000	0.19	2.11
9	5036	High(50)	0.345	0.358	388	99	0.0002	0.20	3.36
10	6555	Zero(0)	0.312	0.329	390	99	-0.0006	0.26	0.67
11	6560	Medium(25)	0.312	0.329	389	99	-0.0006	0.26	2.91
12	6577	High(50)	0.312	0.329	390	99	0.0005	0.25	4.88

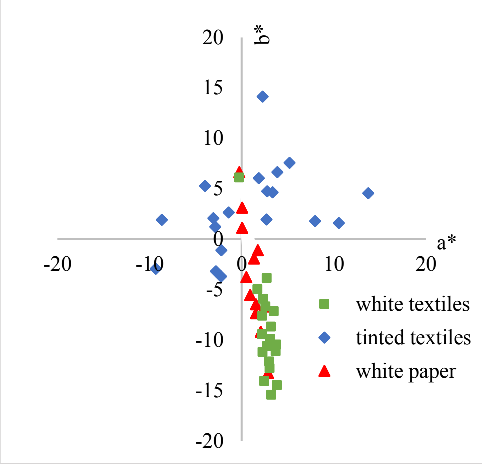

*Figure 2.the sample distribution plotted in a*b* plane in CIELAB colour space.*

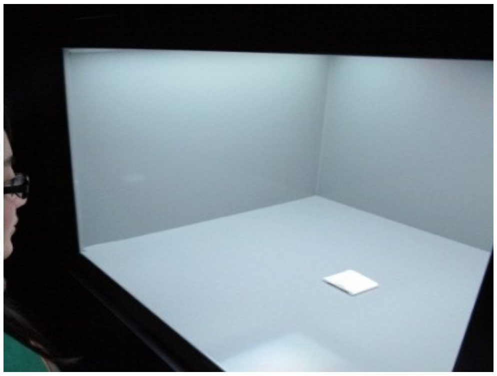

Figure 3.Experimental condition

Figure 3 shows the experimental condition. Samples were placed in the central part of the lighting booth with uniform illuminance distribution. The observers viewed the samples at an illumination viewing geometry of 0°:45° approximately.

Evaluation of whiteness

Three rating scales were used: whiteness, whiteness percentage and hue composition.

Visual scaling

Whiteness has six categories: No trace of white (-3), little white (-2), unacceptable white (-1), acceptable white (1), white (2), pure white (3).

Whiteness percentage and hue composition

Observers were instructed to scale the appearance of each sample in terms of a whiteness percentage scale. It included two components, white and colour, when added together equalled 100. Thus the whiteness percentage of a pure white sample would be 100 and that of no trace of white would be 0. The colour component will be estimated in terms of hue composition, for which the concept of unique hues was used: red, green, blue and yellow. For example, the hue composition of an orange sample could be 60% yellow and 40% red.

Experimental procedure

Before commencing the experiment, observers adapted to the viewing conditions for two minutes. They were then asked to rate the whiteness, whiteness percentage, and hue composition and repeat the results accordingly. The experiment under each lighting condition took approximately 30 minutes. Overall, observers finished the six-hour experiment 6 times in one-week period. Each time lasted one hour.

Measurement

Two instruments were used to make spectral measurements in this experiment: a Datacolor Spectraflash SF600™ spectrophotometer and JETI specbos1211™ tele-spectroradiometer (TSR). All measurements were made using the SF600 under CIE Whiteness calibrated UV conditions, with a large measuring aperture (26mm), di:8° geometry and the specular-component excluded condition. The lighting inside SF600 was a pulsed Xenon D65 simulator. As for JETI, it was used to measure the samples under each phase of the lighting conditions with a 0°:45° geometry. Note that it is typical to measure CIE Whiteness under D65/10° using a sphere based spectrophotometer like SF600 in industry.

The whiteness values of the samples based on the measurements taken with SF600 and TSR were compared. It was found that the whiteness measured using SF600 agreed best with those measured using the TSR under the 6500K with high UV level, but not with those of the other UV levels. This implies that UV energy is essential for accurately measuring whiteness of samples.

RESULTS

Observer variability

The inter-observer variability and intra-observer variability for each scale were evaluated in terms of correlation coefficient (*r*). It should be clarified that high r value in this case means low intra- and inter-observer variability. The intra-observer variability was calculated between the two repeated assessments for each observer. Only the 6500K lighting with high UV level was repeated for all samples. The inter-observer variability correlation value was calculated between the mean and each observer in each lighting phase. The intra- and inter-observer variability in terms of mean r values were (0.890, 0.894) and (0.845, 0.836) for whiteness and white percentage respectively.

Figure 4 shows the plot of whiteness and white percentage results. It can be seen that they have an excellent agreement, and a whiteness of zero (limit of acceptance as white) corresponds to 70% of white percentage. So, 70% whiteness percentage under D65 can be regarded as the visual whiteness boundary.

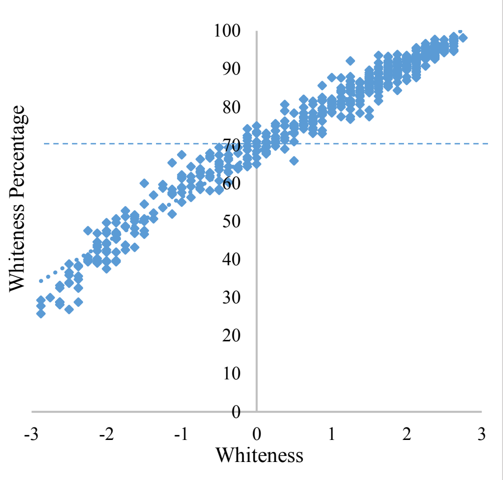

Figure 4.Comparison between whiteness and whiteness percentage.

Testing the performance of the CIE whiteness metric under different illuminants

In this section, various versions of CIE whiteness metrics were derived and tested using the visual data. Here, only the visual results of whiteness-percentage were used because it was found that whiteness percentage attribute to be more consistent than that of whiteness. Whiteness percentage has a 0-100 scale while whiteness only has 6 categories. The correlation coefficient *(r*) was used to indicate the agreement between the metric's predictions and visual results.

$W_{SF\text{-}65}$ and $W_{TSR\text{-}65}$: CIE whiteness index (equation (2)) was proposed to evaluate the whiteness only under illuminant D65/10°. So, the whiteness predictions were calculated from both the SF600 and TSR measurement data under 6500K. The TSR results were only based on the 6500K50UV results (Phase 12 in Table 1) because this phase gave the best agreement to predict CIE whiteness from the SF600 data. By limiting the samples to be within the tint boundary, only 30 samples were considered. These metrics are denoted as $W_{SF\text{-}65}$ and $W_{TSR\text{-}65}$, respectively. They are used to test the visual performance of other lighting conditions besides D65. It can be seen in Table 2 that the two metrics gave similar performance, for which they predicted well for the visual results of middle level UV (25UV), followed by those of the high UV level (50UV). However, it gave very poor prediction to the visual results under no UV content. This implies that regardless how precise the calibration of a spectrophotometer, a source with suitable UV content is highly desired for accurately measuring whiteness.

W_{TSR}: This version calculates the CIE whiteness from Equation (2), having the x_n, y_n chromaticity of the reference white measured under the 12 sources studied. This formula is denoted as W_{TSR}. The results in Table 2 showed that W_{TSR} outperformed those original whiteness metrics in most of the cases, with a mean r value of 0.81.

W_{CAT02}: This version was derived to use a chromatic adaptation transform, CAT02 [15], to transform from the data to D65 from the test illuminants. Subsequently, the original CIE whiteness from Equation (2), having the x_n, y_n chromaticity of 6500K, was used. As shown in Table 2, it is encouraging that W_{CAT02} had the performance equal to or better than W_{TSR} for all phases, although the improvement is small (mean r value of 0.01).

W_O: Another way to improve the CIE whiteness formula was to optimise the values of the constants 800 and 1700 in Equation (2). A general form of the CIE whiteness formula can be expressed as Equation (5):

$$W = Y_{10} + a'(x_{n,10} - x_{10}) + b'(y_{n,10} - y_{10}) \qquad (5)$$

Based on the visual data from each phase, the coefficients were optimized for each CCT to achieve the best performance in terms of *r* values. With CCT increasing, coefficient *a'* decreased and *b'* increased. So the coefficients can be described by Equation (6):

$$a' = -0.1891 * CCT - 2267.2 \qquad (6)$$

$$b' = 0.3202 * CCT - 493.36$$

These functions indicate that a bluish or purplish white will appear whiter than a yellowish or reddish white. As expected, the metric performed well in all phases, giving the same performance as W_{CAT02}.

In conclusion, three indices were developed by modifying the whiteness formula W_{TSR-65}. All three gave similar performance. W_O shows the trend of changing a' and b'—coefficients in Equation (5). Similar to W_{TSR}, there is a need to change the parameters for each illuminant. However, the use of W_{CAT02} would be simpler to transform all colorimetric values from other illuminants to the D65/10° condition, to calculate the whiteness value using the original CIE whiteness metric.

Table 2. The performance of various whiteness metrics base on CIE whiteness metric in terms of the correlation coefficient, r

Lighting Condition	W_{SF-65}	W_{TSR-65}	W_{TSR}	W_{CAT02}	W_O
3000K0UV	0.27	0.29	0.63	0.66	0.74
3000K25UV	0.92	0.92	0.87	0.88	0.87
3000K50UV	0.85	0.85	0.84	0.85	0.84
4000K0UV	0.31	0.33	0.84	0.87	0.84
4000K25UV	0.88	0.88	0.85	0.85	0.85
4000K50UV	0.81	0.81	0.78	0.78	0.78
5000K0UV	0.49	0.53	0.84	0.85	0.84
5000K25UV	0.69	0.70	0.84	0.84	0.84
5000K50UV	0.85	0.85	0.87	0.88	0.88
6500K0UV	0.58	0.60	0.84	0.84	0.84
6500K25UV	0.83	0.83	0.86	0.86	0.86
6500K50UV	0.70	0.70	0.70	0.70	0.70
Mean	0.68	0.69	0.81	0.82	0.82

Whiteness boundary

The tint tolerance of CIE whiteness metric is $-4<T_w<2$ for CIE 10° Observer which was used in the performance test. In Figure 5, all the present data together with 55 additional samples [13] are plotted in CIE 1964 chromaticity diagram under D65. The two parallel red lines and blue lines are also plotted to represent the tint limits $-4<T_w<2$ and ± 5T of whiteness respectively. The red and blue points represent samples with whiteness percentage larger and less than 70% respectively, corresponding to acceptable white and unacceptable white respectively. Figure 5 also shows an ellipse which was fitted to acceptable white data (red points) with 95% confidence interval. The wrong decision percentage (WD%) [16] measure was used to determine the tint limits. It can be seen that the tint limits can be extended to ±5 T to encompass the white tolerance ellipse. Also, the WD% can be reduced from 18% to 6%. This implies that the current limit is too tight.

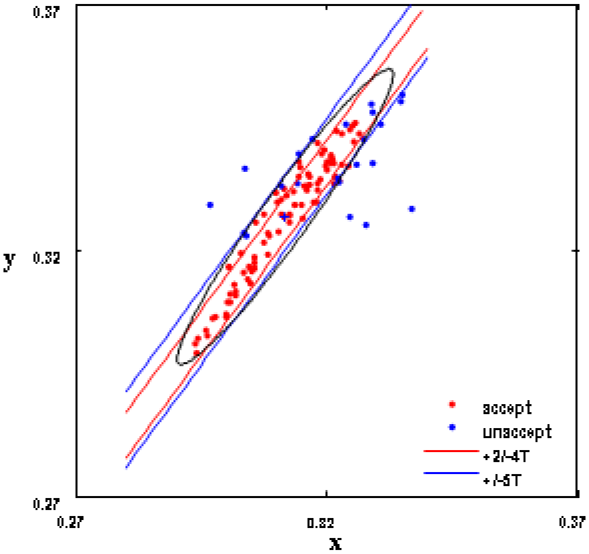

Figure 5. Plot of the data points, the white tolerance ellipse together with the tint limits corresponding to ±5 and -4/+2, respectively.

Conclusion

An experiment was conducted to investigate the whiteness perception under sources having different correlated colour temperature and UV content. The results showed that the two whiteness rating results (whiteness and whiteness percentage) strongly correlated with each other.

The results were used to test and derive various versions of CIE whiteness metrics. Comparing the two versions of original CIE metrics (W_{SF-65} and W_{TSR-65}), they gave the similar performance and fit all data not badly except for those under sources having no UV contents. Comparing the CIE whiteness metric using the variant reference white (W_{TSR}), in general, it outperformed the two original versions.

Two new metrics were derived by either using the CAT02 chromatic adaptation transform (named W_{CAT02}) or optimising the coefficients in CIE whiteness metric for each source (W_O). The results demonstrated that the performance was improved compared to original CIE whiteness. Overall, the three new metrics (W_{TSR}, W_{CAT02} and W_O) can be all considered to be potential candidate for predicting whiteness under different illuminants. The CAT02 version is preferred because it not only predicts the results most accurately for all phases, but also applies the original CIE metric under D65/10°.

As for the tint limit, there is a strong evidence to suggest that the tint limit could be expanded to ±5T. The present finding forms part of the study for CIE TC1-95.

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