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New Metrics for Evaluating Whiteness of Fluorescent Samples

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Abstract

A magnitude estimation experiment was carried out to scale the extent of whiteness from a set of near white textile samples including fluorescent white agent. Each was assessed under 4 different CCTs, each having a high and a low level of UV energy. The results were used to test various existing whiteness formulae. Finally, by fitting to the present data, two new metrics were developed. One is based on CIECAM02, and the other is based on the present CIE whiteness formula by transforming the data to D65 chromaticity from the other white sources via CAT02 chromatic adaption transform with a proper incomplete adaptation factor (D). It was also tested using an independent set of data. Both formulae gave accurate prediction to the data. The former metric is proposed because it is based on a colour appearance model.

INTRODUCTION

Many materials have white colors, such as textiles, papers. They are valued as more valuable, if they have whiter appearance. Hence, whiteness index is important to estimate the degree of whiteness. There are two aspects of white perception. One is associated with the intensity of white, called whiteness, such as snow, normally will be judged as one of the whitest materials. A whiter wool or cotton will be sold a higher price than a less what one. Another is about the neutrality, called neutral white. Neutral colours included from white to black together with a series of grey shades. They do not have little or no trace of hue. Whiteness metrics have been developed over the years [1]. The popular ones including CIE whiteness index have the same structure as shown in Eq, (1).

$$W = Y + \alpha(x_n - x) + \beta(y_n - y) \tag{1}$$

where x,y,Y are the colour specification for the test colour and x_n, y_n are the chromaticity specification of different lighting conditions (D65/10 or D65/2) or different trades. Finally, α and β are the coefficients for the most widely used CIE whiteness indices as listed in Table 1.

Table 1. Coefficients for CIE whiteness indices (Eqs. (1) and (2))

	α	β	γ	δ
CIE-W or T (D65/10)	800	1700	900	650
CIE-W or T (D65/ 2)	800	1700	1000	650

In addition, the white specimens to be evaluated using Eq. (1) are restricted to a certain volume in the colour space. As for CIE whiteness indices, they are defined in Eq. (2) for D65/10 and D65/2 conditions to have -4<T<+2 and 40<W<5Y-280.

$$T = \gamma(x_{10,n} - x) + \delta(y_{10,n} - y) \tag{2}$$

Since the CIE whiteness indices was first adopted in 1986, there have been complaints on its limited illumination to D65 and rather small colour gamut [2]. So, CIE TC1-95 technical committee, the predecessor of TC1-95, the validity of the CIE whiteness and tint equations, has been set up with aims to extend their application to illuminants other than D65 and to review the colorimetric limits hitherto set.

With the above in mind, research collaboration was carried out between Zhejiang and Hong Kong poly universities to respond to CIE TC1-95. Both were equipped with spectrum tunable LED lighting system from visible to UV regions. This allows precise control in the amounts of UV. They have conducted a series of experiments to refine the present CIE whiteness indices [3-5]. Ma at al. [3] first conducted an experiment to include 12 sources at 4 CCTs (3000, 4000, 5000 and 6500K), each 3 UV levels. Eight observers assessed 50 samples including fluorescent whitening agent (FWA) using 3 neutrality scales, white categories (-3 to +3 from no trace of white to pure white, respectively), white percentage (W%) and preferred white. It was found that all three scales had excellent performance. The results were used to derive a neutrality metric as defined in Eq. (3) to predict the neutrality under the 12 sources. In addition, another metric used CAT02 chromatic adaptation transform to predict chromaticity under D65/10 and then used CIE index to predict whiteness. Finally, a tolerance of -5<T<5 was set.

The optimized CIE whiteness formula ($W_{CIE,Optimized}$) is defined by Eq. (3).

$$W_{CIE,Optimized} = Y + a'(x_n - x) + b'(y_n - y) \tag{3}$$

where

$$a' = -0.1891 \times CCT + 2267.2$$
$$b' = 0.3202 \times CCT - 493.36$$

and Y and x, y are the Y tristimulus value and the chromaticity coordinates of a sample under a certain lighting condition, and x_n, y_n are the chromaticity coordinates of the lighting condition.

Also, $W_{CIE,(xn,yn)}$ was also used by calculating using Eq. (1), except that the x_n, y_n are the chromaticity coordinates of the lighting condition in question.

Finally CIE whiteness formula with CAT02 ($W_{CIE,CAT02}$) which used the same equation as W_{CIE}. However, the x, y are the chromaticity coordinates of a sample being transformed to D65/10 from the other sources using CAT02 [8] with an incomplete chromatic adaptation factor (D) set to 1.

Wei et al [4] extended the work to include 105 samples with FWA and non-FWA samples. The same 4 CCTs but only two

UV levels were used. Again, the neutrality category method was used to scale whiteness. The results showed CIE-W plus CAT02 gave the best performance by testing the results from each lighting conditions individually. However, later it was found the scaling methods used were not assessing whiteness intensity but only neutrality. The former and latter can only be used to develop a neutrality index and to define the white boundary, respectively.

Wei *et al.* [5] were then performed another experiment to define white boundary using a set of new data with extremely high UV LED. The intention covered enough white areas but the UV intensity was too high to be practically used in any real light sources.

Wei *et al.* [6] finally carried out an experiment to scale the whiteness binocularly using 4 white samples as reference. Twenty FWA Acrylic samples were assessed by 150 observers under 4 previous CCTs at 1,000 Lux and a low and a high UV levels. Their results showed CIE-W plus CAT02 with proper set of incomplete adaptation factors. It can reach a correlation coefficient of 0.937, than all the other metrics.

The present experiment was performed about the same time as Wei et al [6]. The goals were to produce new experimental results using different scaling techniques to verify the Wei et al data and to derive a new whiteness index.

The goals of this study are to generate a set of robust data, to test different formulae and to propose a formula for industrial applications.

EXPERIMENTAL

Light settings

The light sources used here was a multi-channel LED illumination system supplied by the ThousLite Ltd. It was composed of 11 monochromatic LEDs and 3 LED white phosphor lightings. It was controlled by a software which is used to adjust various lighting quality parameters.

This study used 8 light sources including four CCTs (6500K, 5000K, 4000K, 3000K) and two UV levels for each CCT (designated as medium and high). The Ra values of all the sources were all above 95 and the variations of Duv and were ± 0.001 and ±50K. The colorimetric characteristics of the light settings are shown in Table 2.

Table 2. The colorimetric characteristics of the light settings

	CCT	$D_{uv}(10^{-4})$	R_a	MI_{vis}	MI_{uv}
6500K-m	6289	-3	97	0.4143	4.4765
6500K-h	6306	-6	97	0.6547	3.9881
5000K-m	4876	30	97	0.3536	2.7764
5000K-h	4889	27	97	0.8284	2.1640
4000K-m	3957	5	98	-	-
4000K-h	3958	4	98	-	-
3000K-m	2888	1	96	-	-
3000K-h	2889	1	96	-	-

The medium level was set up to have a match of the whiteness values for 10 fluorescent samples to those measured by a Datacolor SF600 spectrophotometer, for which its UV amount was calibrated via a set of reference standards. The high UV level was about 1.5 times than that of middle level in W/(sr*sqm*nm) units which would make samples to appear obvious tints. Figure 1 shows the spectral power distribution (SPD) of the 8 light sources used in the experiment.

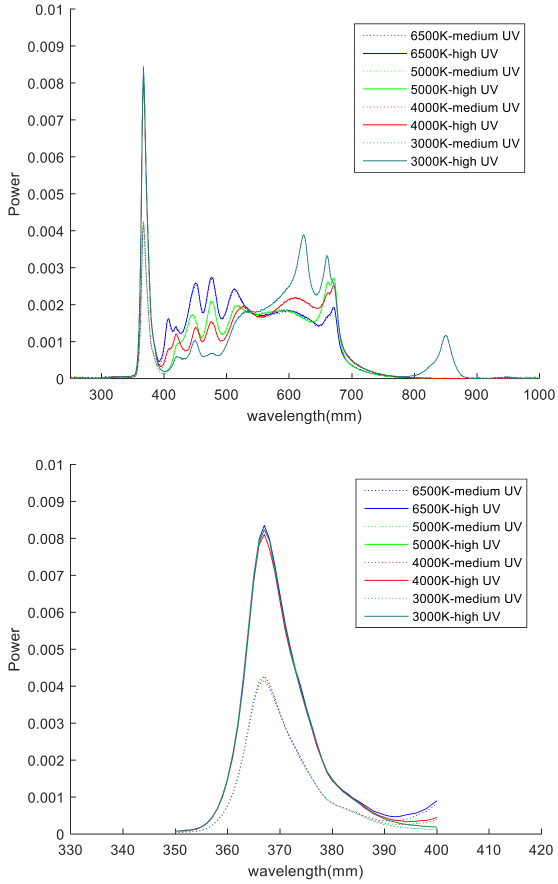
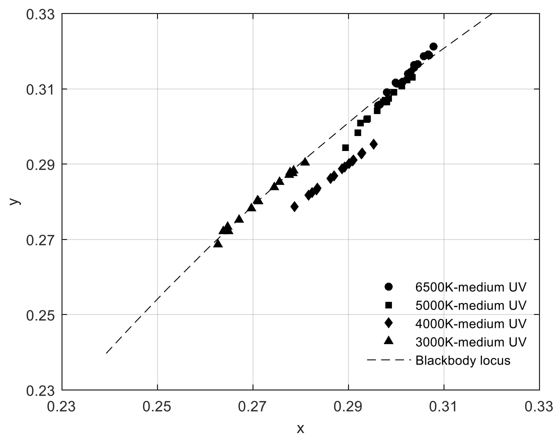


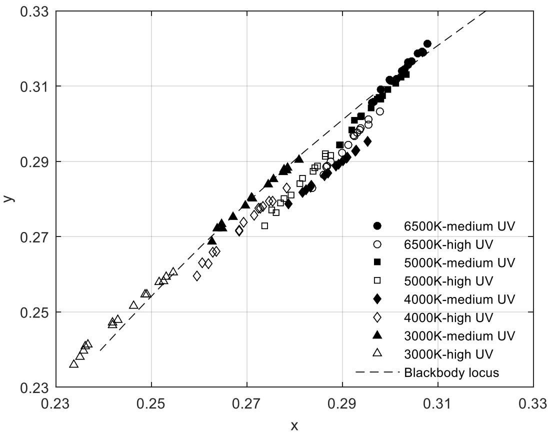
__Figure 1.__ SPDs for 8 lighting conditions and their enlarged region between 350 to 400 nm.

Samples

The experiment was divided into 2, denoted as Experiment 1 and Experiment 2 respectively. Six of them were used in Experiment 1 and 15 of them were used in Experiment 2. Two samples were evaluated in both experiments. Figure 2 shows the distribution of all samples in the a*-b* and a*- W_{CIE} plane which was measured by a JETI 1211 tele-spectroradiometer, whose spectral coverage was ranged from 250 to 1000 nm at a 5 nm interval.



(a)



(b)

Figure 2. *The chromaticity coordinates of the samples under (a) 4 lighting conditions and (b) 8 lighting conditions.*

Figure 2 show the chromaticities of the whiteness samples under different light settings calculated using the CIE 1964 10° CMFs. Figure 3 show the sample distribution in CIELAB a*b*, plane.

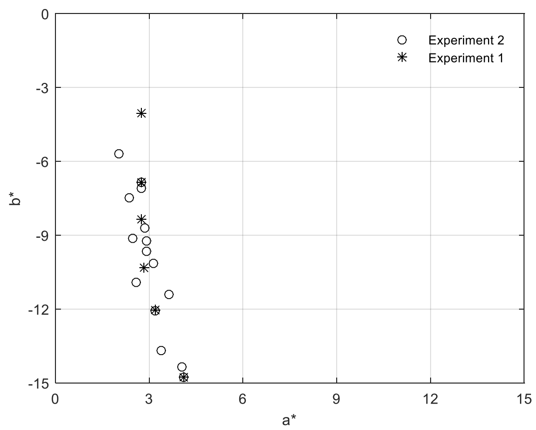


Figure 3. *Distribution of all samples in CIELAB a*b* plane.*

Observers

Twenty observers (10 females and 10 males) between 21 and 26 years of age (mean = 22.05) took part in Experiment 1. Twenty observers (13 females and 7 males) between 19 and 26 years of age (mean = 20.5) took part in Experiment 2. All of them had normal color vision tested by Ishihara color vision test.

Visual assessment

Two viewing cabinets were used in the experiment, one for viewing the reference sample and the other for viewing the test samples as shown in Figure 4. Observers viewed both samples using the 0^o:45^o illumination:viewing geometry.

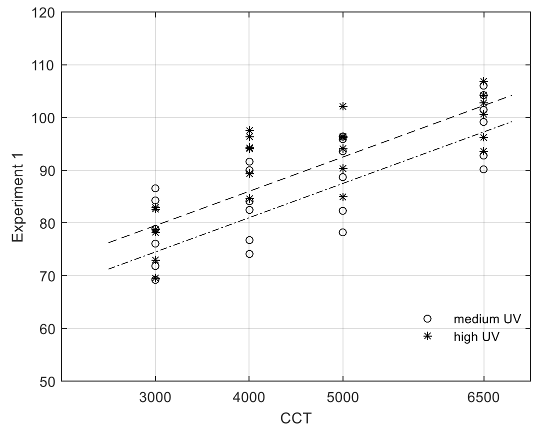
This study is divided into two experiments. The 'consecutive memory' and 'session memory' magnitude estimation methods were used for Experiments 1 and 2 respectively.

In Experiment 1, observers were asked to look at a standard sample in the reference cabinet (the left one in Figure 4 under a D65 fluorescent simulator) for one minute and then adapted to the lighting in the test cabinet for another minute and assess the whiteness value of the all 6 test samples under each of the 8 lighting conditions. When changed to a new lighting condition, the above process started overall again. The standard sample was assigned to have a whiteness value of 100. In Experiment 2, observers were asked to assess 15 test samples under the same 8 lighting conditions. However, the reference cabinet could not be viewed all the time during the experiment. Observers were asked to memorize the standard sample having a 'whiteness' of 100 in the reference cabinet at the beginning of each session and then re-adapted in the test cabinet for all sources. The whiteness of all the colors were then assessed against that in the memory. If observer forgot the standard during the experiment, s/he would look the standard sample under the reference cabinet and the whole process would start all over again.

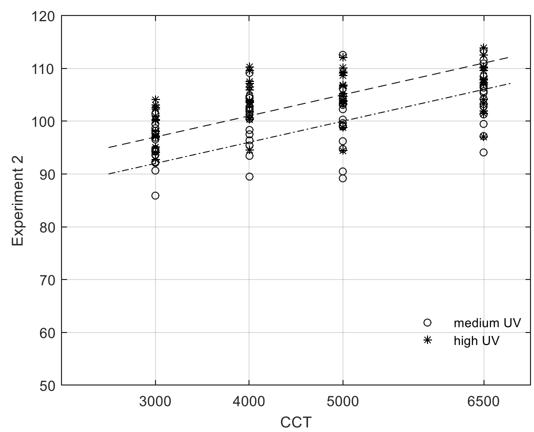
Figure 4. *Two cabinets used (left is the reference one and right is the testing one).*

RESULTS

Figures 5a and 5b show the estimation results for Experiments 1 and 2, respectively, together with the best fitted line for each UV level.



(a)



(b)

Figure 5. *A plot of whiteness results against CCT for (a) Experiment 1 and (b) Experiment 2*

Each figure clearly showed that within the same UV level, a higher whiteness values under a higher CCT source. And within the same CCT, samples appear to be whiter under lighting with higher UV level.

Comparing with the results of two experiments, it can be concluded that the whiteness of a sample is increased under a source to have a higher CCT or higher UV. In addition, whiteness perception revealed that samples ha d different chromaticity values under lighting conditions with different UV levels.

Inter- and Intra- observer variability

Estimations were made using consecutive memory matching and session memory matching respectively. Figure 6 shows the results obtained from the two samples, repeatedly assessed in both experiments. It can be seen that Experiment 2 results are higher than those of Experiment 1. The slope of 0.92 was found between two sets of data and it was used to combine two sets of experimental results.

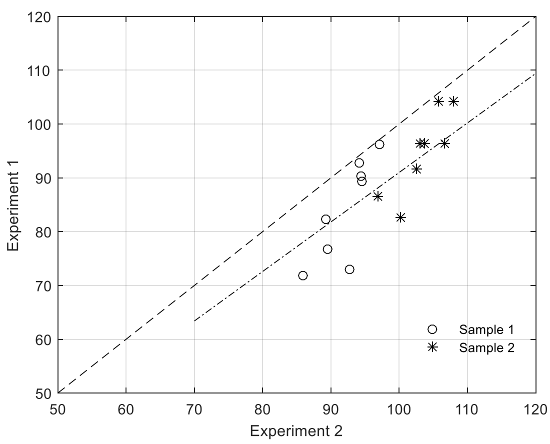


Figure 6. Whiteness estimation for the two repeated samples (Sample 1 from Experiment 1, Sample 2 from Experiment 2).

It is obvious that the correlation between the two experiments is relatively high but the overall whiteness of Experiment 2 is higher than Experiment 1. This was caused due to the viewing condition, i.e. luminance and neutral grey background colors used in both experiments are different and the assessment methods used, i.e. the effect of chromatic adaptation.

Inter-observer variability was also analyzed. Table 3 shows the inter-observer variability results between two experiments. This was calculated using STRESS measure The STRESS value calculated from equation (1) was used to indicate the disagreement between A and B datasets.

$$STRESS = \left(\frac{\sum_{i=1}^{n} \left(A_i - FB_i \right)^2}{\sum_{i=1}^{n} F^2 B_i^2} \right)^{1/2} \times 100 \qquad (4)$$

and $F = \sum_{i=1}^{n} A_i^2 / \sum_{i=1}^{n} A_i B_i$

where n is the number of samples and F is a scaling factor to adjust A and B data sets on to the same scale. The percent STRESS values are always between 0 and 100. Values of STRESS near to zero indicate better agreement between two sets of data. In colour-difference studies, a STRESS value exceeding 35 is typically an indicator of the poor performance of the colour-difference formula [12].

Table 3. Inter-variability of two estimations

STRESS	Experiment 1	Experiment 2
6500M	14	9
6500H	17	9
5000M	16	9
5000H	17	10
4000M	15	9
4000H	15	9
3000M	14	11
3000H	17	11
Mean	15	10

From Table 3, it can be seen that the mean STRESS value clearly showed that Experiment 2 method is much more consistent than Experiment 1 results by a factor of 1.5. Overall, the session memory method is more reliable than that of consecutive memory method. This implies that the chromatic adaptation had a big impact to visual assessment. In addition, the session memory method can save large amount of experimental time without doing re-adaptation all the time.

Development of a whiteness formula

After various trials, equation (5) was adopted with the similar structure of current CIE whiteness formula (equation (1)).

$$W_{Jab} = g_1 J' + g_2(a'_c - a') + g_3(b'_c - b') \qquad (5)$$

where CAM16-UCS *J', a'* and *b'* are the values of the sample and a'_c and b'_c are the values for the neutral white, respectively. In addition, the D factor in the model was also changed according to different CCT used in the experiment. Note that the *g* coefficients, a'_c, b'_c and D factors were optimized for each of the two data sets.

The advantages to include CAM16-UCS are first to allow all colours to be transformed to those under the reference illuminant SE, and second to calculate lightness (*J'*), $\Delta a'$ and $\Delta b'$ in its uniform colour space, for which these 3 terms were found to be most significant for assessing the whiteness, i.e. the lighter the colour, the closer to the neutral white defined by [a'_c, b'_c], the whiter the colour will be.

After fitting the present data, the final whiteness formula is given in equation (6).

$$W_{Jab} = J' + 0.295(-0.81 - a') + 4.135(-2.58 - b') \qquad (6)$$

where the incomplete adaptation factors in CAM16-UCS used are 0.34, 0.46, 0.48, 1.0 for 3000K, 4000K, 5000K and 6500K, respectively.

Finally, all formulae were tested using the present dataset. Table 4 lists the STRESS values of the W_{CIE}, $W_{CIE,(xn,yn)}$, $W_{CIE,Optimized}$, $W_{CIE,CAT02}$, $W_{CIE,CAT02,D}$ and $W_{CIE,Jab}$, the proposed one. Generally, $W_{CIE,CAT02,D}$ and $W_{CIE,Jab}$ had the best performance, i.e. lowest STRESS values. The result indicates the incomplete adaptation under other lighting conditions with lower CCT, which is consistent with the findings from other researches.

Table 4. Performance of the whiteness formulae

Formulae	STRESS
W_{CIE}	11
$W_{CIE,(xn,yn)}$	26
$W_{CIE,Optimized}$	22
$W_{CIE,CAT02}$	27
$W_{CIE,CAT02D}$	38
W_{Jab}	6

There is another data set was published for the evaluation of whiteness under different illuminants at different UV levels, i.e. the present and that produced by Wei *et al.* [13] at the Hong Kong polytechnic University. Their data included 8 specimens which were assessed under 3 CCTs, each at a high and a low UV level. Magnitude estimation method was used to judge the whiteness by 15 observers against a group of 4 reference samples marked the CIE whiteness values under Haploscopic viewing condition. Observers estimated the whiteness by interpolation of the whiteness values between the reference samples.

Equation (6) was also tested using the Hong Kong Polytechnic data. However, it was found that equation (6) gave a poor fit to the data, i.e. STRESS value of 25 comparing with that of 6 in Table 4. Further investigation will be carried out to reveal the difference between the two data sets.

CONCLUSION

Two psychophysical experiments were conducted to assess whiteness perception using the successive and session memory magnitude estimation methods. Twenty observes evaluated the whiteness appearance of 6 samples under eight light settings at different CCT levels (i.e. 3000, 4000, 5000, and 6500K) and different UV levels (medium and high) generated using a multi-channel spectrally tunable LED device.

It was found that the two sets of results agreed well with each other. They all revealed that whiteness increases accompany by an increase of CCT and UV contents. A new white formula W_{Jab} was proposed which proved to have the best performance. However, the formula cannot predict well to the Hong Kong data sets. Efforts will be spent to find the difference between the two data sets.

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