Assessing the Quality of Two LED Based CIE Illuminant Simulators

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Abstract

CIE D50 and A simulators based on a multi-channel LED system were evaluated and compared with those based on conventional fluorescent and tungsten sources. A psychophysical experiment was carried out for critically evaluating the colour difference of 30 metameric pairs. The results showed that LED lighting based on 9 channels can successfully achieve the desired quality specified by ISO 3664:2008(E) viewing conditions for the applications of graphic technology and photography. In the visual experiment, it was found that LED simulator outperformed the conventional fluorescent simulator under D50 illuminant, and gave similar performance as the tungsten simulator under A illuminant.

Introduction

The lighting industry is going through a phase of revolution. LED lighting is now widely spread not only to replace the existing tungsten and fluorescent lamps due to its low electricity consumption, longer life and greener energy, but also to produce smart lighting because of its tunable spectrum to achieve the desired lighting quality for different applications. For industrial visual inspection, products are typically based upon conventional CIE illuminant simulators such as filtered tungsten, fluorescent and few apply multi-channel LED. Although these LED systems are based on limited LED channels, they may have similar visual appearance when seen against CIE illuminants. This paper describes a visual experiment to evaluate the quality of an LED apparatus for assessing colour difference.

Two standard illuminants (D65 and A) are specified by the joint ISO/CIE standard [1] in terms of the spectral power distribution (SPD). In the graphic and imaging industries, the standard viewing conditions are specified by ISO 3664:2008(E) [2] with standard CIE D50 illuminant. It provides standard conditions for viewing graphic art prints, transparencies and displays. It defines the standard viewing conditions in terms of the u_{10}', v_{10}' chromaticity, correlated colour temperature (CCT), illuminance, colour rendering index, metamerism index in the visible and UV ranges of spectrum, uniformity, and reflectance of the neutral surround. It specifies the u_{10}', v_{10}' values [0.2102, 0.4889] at 5000K. Also, it specifies the deviation from 5000K from the blackbody locus within ±0.005 Du'v' units. There are two illuminance levels for viewing prints, 2000 or 500 lux for critical and ordinary viewings, respectively.

ISO 3664 applies two measures recommended by the CIE to ensure the quality of lighting, colour rendering index CIE-R_a [3] and metamersim index [4]. Colour rendering index is used to measure the colour change of one sample viewing between a test illuminant and a reference illuminant in terms of a colour difference formula such as CIELAB [5]. The reference illuminant is defined as a chromaticity on the CIE daylight or blackbody locus [5]. A perfect colour rendering lighting will have CIE-R_a of 100, or zero colour difference between under the test and reference illuminants. ISO 3664 specifies CIE-R_a to be ≥90 and each of the 8 test samples should have R_i ≥80.

The metamerism index, also defined by CIE [4], is used to measure the colour difference between pairs of virtual metamer, which are defined as the spectral reflectance for each pair of samples. CIE defines 5 and 3 virtual pairs of spectral reflectance functions for the visual and UV spectrum, respectively. They were designed to have a close to zero colour difference under CIE daylight illuminants such as D50 illuminant with and without UV. ISO 3664 specifies M_V and M_U indices, to have mean ΔE^*_{ab} ≤1.0 and ≤1.5 for visual and UV regions, respectively. They are reported in Grades A, B, C, D, E corresponding to mean ΔE^*_{ab} values of 0.25, 0.5, 1.0, 2.0 and >2.0, respectively. Both CIE-R_a and M_V measures are used here to indicate the quality of CIE illuminant simulators. The results of M_U will be reported elsewhere.

Comparing the Performance in terms of $D_{u'v'}$, CIE-R_a and M_V

Two sources were investigated to simulate CIE D50 and A illuminants using an LED apparatus (named LED-D50 and LED-A respectively), and another two sources were also investigated using traditional fluorescent and tungsten lamps to simulate CIE illuminants (named F8 and T respectively). The LED simulators here were generated by an LED lighting system having 9 channels covered the visible spectrum. The LED-D50 was built to strictly follow the specification of ISO 3664. LED-A is aimed to reproduce CIE A illuminant also using the LED lighting system. The other two simulators include a typical FL8 fluorescent lamp and a tungsten bulb, representing the majority of products in practice. A database was prepared to store the luminance levels for each LED channel in the lighting system. Software was used to match the target spectrum with the desired lighting parameters including spectral power distribution (SPD), u', v', cd/m^2, CIE-R_a and M_V.

The engineering data of the 4 simulators are summarised in Table 1 together with the standard specifications for CIE D50 and A illuminants. It can be seen that the LED-D50 simulator passed but the F8 tested failed the $D_{u'v'}$ tolerance according to ISO3664, i.e. less than 0.005. For CIE illuminant A, both simulators gave similar performance, but the T simulator performed slightly better than LED-A simulator in $D_{u'v'}$ and CIE-R_a. Overall, all simulators achieved CIE-R_a above 90. For the M_V measure, it can be clearly

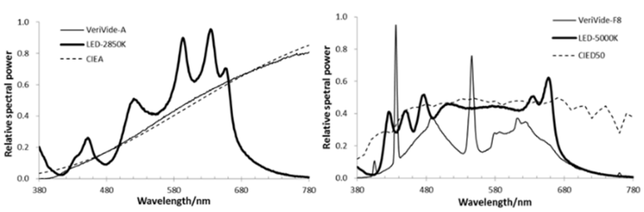
Table 1 The engineering data for the four simulators studied together with two CIE illuminants including u', v', luminance (cd/m²), CIE-R_a and M_V

	CCT (K)	u'	v'	$D_{u'v'}$	cd/m²	CIE-R_a	M_V(CIELAB)
CIE-D50	5000	0.2102	0.4889				
LED-D50	4926	0.2104	0.4887	0.0003	154	98.5	0.27
F8	4829	0.2152	0.4842	0.0069	154	94.2	0.80
CIE-A	2850	0.2559	0.5244				
LED-A	2847	0.2553	0.5293	0.0049	156	93.4	n/a
T	2840	0.2557	0.5285	0.0041	156	97.7	n/a

seen that LED-D50 markedly outperformed the F8 and can achieve almost Grade A (CIELAB of 0.25 units).

The SPD of each simulator is given in Figures 1a and 1b together with the targets of CIE-A and CIE-D50, respectively.

It can be clearly seen in Figure 1a that the SPD of the T simulator is much closer to that of CIE-A compared with LED-A. However, LED-A can still achieve a close CCT match and high CIE-R_a as shown in Table 1. As for the two D50 illuminators in Figure 1b, the variation of SPD is larger for F8 than LED-D50.



(a) (b)

Figure 1. The SPD of the four simulators together with two CIE illuminants investigated in the experiment a) T; LED-A; CIE A, b) F8; LED-D50; CIE-D50

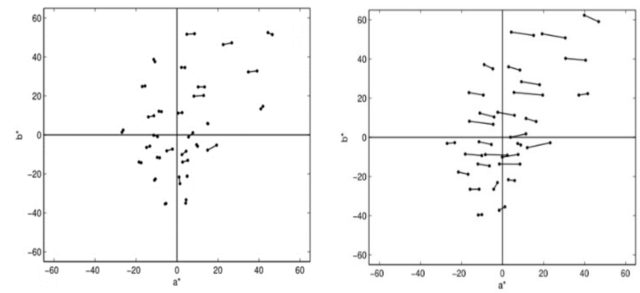
Experimental

A psychophysical experiment was carried out to verify the performance of the 4 CIE illuminant simulators.

Sample preparation

The experiment was designed to test the performance of CIE illuminant simulators by assessing colour difference pairs. For a good agreement between a CIE illuminant and its simulator, each colour difference pair should have the same perceived colour difference under both illuminants. Thirty colour difference pairs, which are also called metameric pairs, prepared by Kuo and Luo [6] to study metamerism were used here. Normally, a metameric pair (or metamer) is consisted of one colour constant and one colour inconstant sample, for which their spectral properties are different. They are specially designed that one to have consistent appearance and the other inconsistent appearance under different illuminants. These pairs were specially prepared to have small colour difference under daylight illuminants such as D65, D50, and large colour difference under F11 or A illuminant, or both of them. The mean colour difference of thirty metamers under D50 and A are 2.44 and 7.17 in CIELAB colour space respectively.

Figures 2a and 2b plot the 30 metamers in CIELAB a*b* diagram under CIE-D50 and CIE-A respectively. It can be seen that the vectors are much smaller under CIE-D50 than those under CIE-A. Also, the colour shift for each vector under the CIE-A illuminant was always along the a* axis (red-green direction).



(a) (b)

Figure 2. Sample distribution under a)CIE-D50 and b)CIE-A

Psychophysical methods

The grey scale method [7] was used based on the ISO 105: Part A03 grey scale for assessing staining. Each pair was assessed against 9 sample pairs in a grey scale ranged from 1 to 5 at 0.5 interval from large to no colour difference. Ten observers participated in the experiment. They all passed the Ishihara colour vision test. Their average age was 25 ranged from 21 to 35 with a standard deviation of 4.04. Each observer was asked to rate the colour difference against the grey scale. They were encouraged to give decimal grades, e.g. Grades of 2.8 and 3.2 have 0.2 grade units larger and smaller perceived colour difference respectively than that of Grade 3.

Overall, 1200 colour difference judgements have been done, i.e. 10 observers x 30 pairs x 4 illumination conditions.

Results and Discussion

The raw data were first transformed to visual colour difference (ΔV). The ΔV was obtained by transforming each observer's Grade data via a polynomial equation fitted between Grade number and ΔE^*_{ab} colour difference of each grade in the grey scale (see Reference [7]).

Inter-observer variability

The STRESS measure [8] was used to indicate the inter-observer variability for assessing colour difference in this experiment. For investigating each observer's performance, the STRESS value was calculated between his/her ΔV results and the averaged ΔV results of ten observers. STRESS values can be regarded as disagreement percentage between two datasets. For example, a STRESS value of 30 means 30% disagreement between two datasets. Thus, a larger STRESS value means a worse agreement and a larger inter-observer variability. It was found that the STRESS values for ten observers ranged from 21 (the best) to 43 (the worst) with a mean value of 31. This performance is similar to that of the experiments conducted for evaluating colour difference formulae [9]. Their results, which involved 450 pairs surrounding 17 colour centers with a mean colour difference of 3.0 ΔE^*_{ab} units, using grey scale method have inter-observer variability of 31 STRESS units. Moreover, the ten observers' STRESS values under one simulator were averaged to represent the variation for this simulator. Comparing the 4 simulators investigated in this experiment (T, F8, LED-A and LED-D50), they all gave very similar performance with a mean of 31 STRESS units ranged from 30 to 32.

Testing the performance of simulators using metamers

The visual results under each simulator were first used to test the performance of CIELAB [5], CIEDE2000 [10] and CAM02-UCS [11] colour-difference formulae. The first two are the current CIE uniform colour space and colour difference equation. The latter is an extension of CIE 2002 colour appearance model (CIECAM02) [12] to give similar performance of accuracy as CIEDE2000 but also imbedded with a chromatic adaptation transform and a uniform colour space. (Note that most of these spaces and equations are developed under daylight illuminants. In the current study, colour differences under illuminant A were also evaluated.) The test was conducted to investigate models' performance to fit the experimental data. The actual SPDs of the four simulators were used to calculate the theorical colour differences between metamers using the 3 models. Afterwards the STRESS values calculated between the predicted colour differences and visual colour differences indicate the models' performance. The results in terms of STRESS values are summarised in Table 2. Note that smaller STRESS value means less prediction errors and better agreement.

Table 2 Models' performance in predicting colour difference results

STRESS	F8	LED-D50	T	LED-A
CIELAB	37	40	26	26
CIEDE2000	30	28	19	19
CAM02-UCS	30	28	20	18

It can be seen that for each of the 4 simulators, CIEDE2000 and CAM02-UCS gave similar good performance with similar STRESS values. Moreover, they both markedly outperformed CIELAB, which showed more prediction errors with larger STRESS values. It was also found that the STRESS values of all models except CIELAB are less than that of inter-observer variability (31) under LED simulators. This implies that all models except CIELAB can predict metameric pairs under the two D50 simulators more accurately than the typical observer variability based on a panel of 10 observers. Thus, it can be concluded that CIEDE2000 and CAM02-UCS showed reliable performance in predicting colour difference results. In addition, comparing the results between D50 and A simulators, the STRESS values from the former simulators are larger than those of the latter simulators. This is due to the metamers exhibit larger colour difference under the latter than under the former. The effect is well known that observers judge smaller colour differences less accurately than judge larger colour differences.

Table 3 Models' performance in agreement with CIE illuminants

STRESS	CIE-D50		CIE-A	
	F8	LED-D50	T	LED-A
CIELAB	44	36	26	28
CIEDE2000	38	21	20	20
CAM02-UCS	40	24	21	19

The second test was conducted to evaluate the performance of the simulators studied against the CIE illuminants. Again, CIELAB, CIEDE2000 and CAM02-UCS were used. The SPDs of the two CIE illuminants were used to calculate colour differences between metamers using the 3 models. The STRESS values were again employed to indicate the performance of simulators, which were calculated between the predicted colour differences under CIE illuminants and visual results obtained under CIE simulators (see Table 3). It can be seen that LED-50 performed much better than the conventional F8 fluorescent lamp, while LED-A and T gave similar performance. It is encouraging that although the LED-A appears quite different from CIE-A in their SPDs, the results showed that their visual differences gave very similar results.

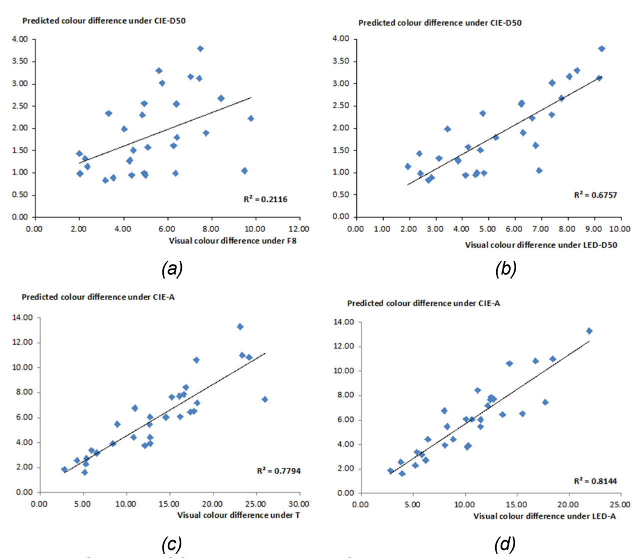


Figure 3. CAM02-UCS predictions under CIE illuminants against visual colour differences under 4 simulators for a) CIE-D50 vs F8, b) CIE-D50 vs LED-D50, c) CIE-A vs T and d) CIE-A vs LED-A

The effect can be clearly seen in Figure 3 by plotting the CAM02-UCS predictions under CIE illuminants against visual colour differences (ΔVs) for the 4 simulators: a) CIE-D50 vs F8, b) CIE-D50 vs LED-D50, c) CIE-A vs T and d) CIE-A vs LED-A, respectively. The best fitted line together with the R^2 values are also given in Figure 3. The points in Figure 3b have better linearity than those in Figure 3a. This also means that visual results under LED-D50 correlated with predicted results under CIE-D50 better than F8 simulator. On the whole, these scatter diagrams provided further evidence of the conclusions in Table 2, i.e. LED-D50 outperformed the F8 simulator, and LED-A gave similar performance as the T simulator.

Conclusions

Four CIE illuminant simulators were evaluated using the criteria specified by ISO 3664:2008(E). The measurement results showed that LED-D50 outperformed F8 by large margin, especially on CIE metamerism index. LED-A performed about the same as T simulator. In the psychophysical experiment, 30 metamers were assessed by 10 observers under the four simulators. The results clearly indicate that LED simulators performed equal to tungsten based CIE-A simulator or better than fluorescent lamp based CIE-D50 simulator so that it can be reliably used for industrial visual inspection.

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