Evaluation of Light Sources Based on Visual Colour Rendering

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Abstract

The CIE colour rendering index (CRI) has been used to test the colour rendering properties of light sources for over 30 years. However, this method is outdated and problematic, especially for evaluating white light emitting diodes (LEDs) [1]. In present work, the current CIE Test Method has been investigated by comparing visual colour rendering of test samples between LED light sources and a reference fluorescent lamp. The results show that CIE CRI is not good enough to predict visual perception. Moreover, the method was modified based on CAM02-UCS [2], and it provided better correlation between visual and predicted colour rendering values.

Introduction

Colour rendering is defined as an "Effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant" [3]. The currently recommended CRI was officially introduced in 1974. In the CIE test-colour method, samples illuminated by the test source and the reference illuminant with the same colour temperature are compared and the colour differences are calculated in the U*V*W* colour space. A von Kries chromatic adaptation transformation is applied if the chromaticity between the test source and the reference illuminant is different.

However, this method is outdated and problematic. First of all, the CIE 1964 U*V*W* uniform colour space used to calculate colour differences is outdated with the particularly non-uniform in the red region. The von Kries chromatic adaptation transform used in the CRI perform poorer than other available models, such as the CAT02 included in the CIE 2002 colour appearance model, CIECAM02 [4]. Moreover, none of the eight reflective samples used in the computation of CRI are highly saturated. This is problematic because the colour rendering of saturated colours could be very poor even when the CRI value is good, especially for the peaked spectra of white LEDs [5].

Therefore, in this study, the performance of CIE CRI has been tested. The visual colour differences of test samples between test light sources and a reference light source were evaluated by observers, and the results were compared with the CIE Test Colour method predictions. A fluorescent lamp supplied by VeriVide Ltd was used as the reference lamp due to its high colour rendering index and high metamerism category in visible range. The test sources were developed based on LEDs.

The LED applications have grown tremendously due to its long life span, high energy efficacy and durability, etc. Moreover, a wide variety of LEDs with different peak wavelengths covering the visible region are now available. With this in mind, a spectrally tunable LED cluster consisting of eight LEDs was constructed [6]. The spectral power distribution (SPD) of this LED cluster could be adjusted by controlling the radiometric output of each LED individually. Thus, it is able to simulate any CIE D illuminants with high CRI value and high metamerism category. In this study, four test sources were developed by the LED cluster. These four test sources have similar correlated colour temperature (CCT) and chromaticity as the reference lamp, but have different CRI values. Table 1 shows the colorimetric results for both reference lamp and test sources, and Figure 1 shows the SPDs results.

	CCT (K)	x	y	R_a	M_v (ΔE^*_{ab})
Reference lamp	6757	0.3089	0.3247	96	B(ΔE^*_{ab} =0.50)
Test source 1	6883	0.3075	0.3206	99	A(ΔE^*_{ab} =0.21)
Test source 2	6965	0.3064	0.3196	81	D(ΔE^*_{ab} =1.07)
Test source 3	6803	0.3088	0.3207	80	E (ΔE^*_{ab} =3.16)
Test source 4	6702	0.3108	0.3195	52	E (ΔE^*_{ab} =4.82)

Table 1 Colorimetric results for reference lamp and test sources

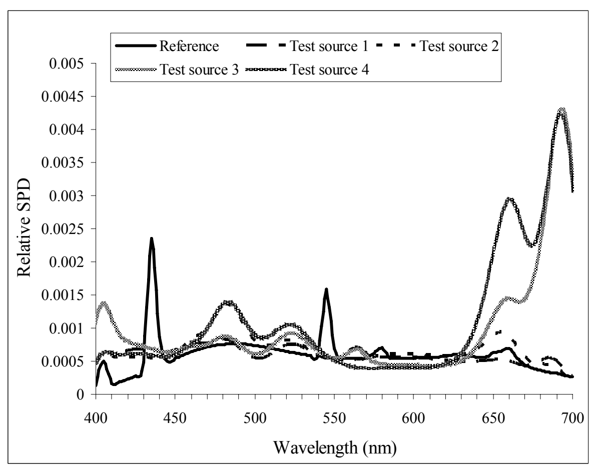

Figure 1 SPDs results for reference lamp and test sources

Table 1 shows that the four test sources have very close CCT and chromaticity as the reference lamp. Meanwhile, the test sources have different CRI values, ranging from 52 to 99. Test sources 2 and 3 have very close CRI values, and the difference is that, test source 3 has much more spectral power in the blue and red region than test source 2, as shown in Figure 1. Therefore, the colour distortion in red and blue region under test source 3 is much larger than that under test source 2.

Visual Experiment

Fifteen highly colour inconstant samples which were prepared by Kuo and Luo [7] were used. These samples were chosen due to their large inconstancy values between the test sources and the reference lamp calculated using a colour inconstancy index CMCCON02 [8]. Therefore, a considerable change in colour appearance was observed when the samples were viewed first under the reference lamp and then under the test source with low a R_a value, such as test source 4. Figure 2 shows the colour appearances shift from the reference lamp to the test source 4 in CAM02-UCS a'b' plane. If samples are colour constant, each vector in Figure 2 should be a point. It can be seen that most of non-colour constant samples are located in two ends of *a'* (redness-greenness) axis.

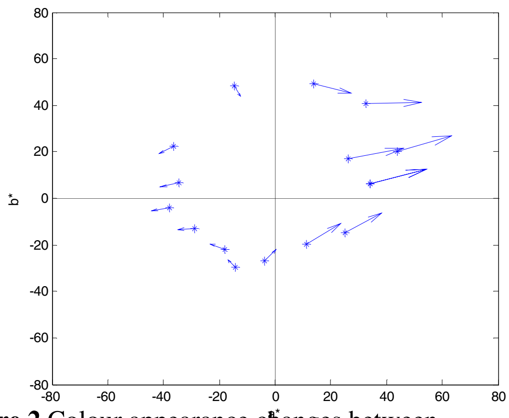

Figure 2 Colour appearance changes between reference lamp (asterisk) and test source 4 (arrow end).

Two very similar booths were placed side by side as shown in Figure 3, where in left-side booth the reference lamp illuminated the samples, and in right-side booth test sources were installed. The walls and bottom of both cabinets were covered by a black fabric in order to make the background exactly the same. A large black cardboard was placed between the two booths in order to block the light from each other. Ten observers with normal colour vision participated in this experiment.

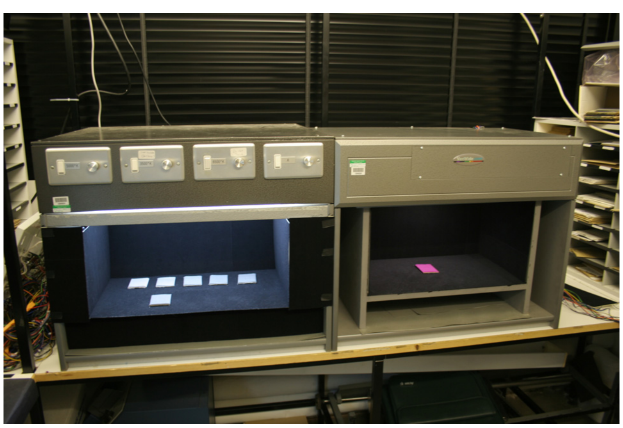

Figure 3 Two viewing booths for visual colour differences assessment.

The task of observers was to scale the visual colour difference between the corresponding test colour. A similar experiment has been conducted by Sándor [9], in which observers were permitted to look into one or the other booth simultaneously several times before they made their judgment. However, observers cannot be fully adapted to neither the test source nor the reference lamp in Sándor's experiment. Thus, in our experiment, observers were first asked to adapt to the test source for 15 seconds [10] and remember the colour of a randomly selected sample; afterwards, they were adapted under the reference lamp for another 15 seconds. After re-adaptation under the reference illuminant, the test sample was shown again, and observers were asked to estimate the colour difference between the colour seen under reference lamp and that memorised colour by using grey scale method. If observers have forgotten the colour previously seen under the test source, they were allowed to see the test sample again, but 15 seconds adaptation time under both test source and reference lamp would be applied.

Results and Discussions

Each sample was evaluated twice by observers, and finally 1200 visual colour difference data (15 samples×10 observers×4 test sources×2) have been collected. The visual data were compared to the calculated colour difference in U*V*W* colour space as defined in CIE test-colour method. Moreover, other colour difference formulae have been tried, and the CAT 02 chromatic adaptation transformation has been applied to abridge the chromaticity difference between test source and reference lamp.

Table 2 shows the correlation coefficient between visual data and different colour difference calculation methods. It can be seen that the colour difference calculation based on CAM02-UCS gives the best performance, and it can predict the visual colour difference much better than the original method used in CIE CRI. The CV value has been improved from 57 to 39 and the correlation coefficient has been improved from 0.85 to 0.92 by using CAM02-UCS.

Colour difference formulae	CIE U*V*W*	CIELAB	CIECAM02	CIE CAM02-UCS
Correlation coefficient	0.85	0.89	0.91	0.92
CV	57	42	43	39

Table 2 Performance of difference colour difference formulae

In Figure 4, the visual colour differences were plotted against the calculated colour difference in U*V*W* colour space for each test source and Figure 5 plots the visual colour differences against the calculations based on CAM02-UCS. It can be seen that the agreement between visual data and CAM02-UCS predictions is better than that between visual data and CIE CRI predictions as shown in Figure 4. Thus, we can say that the colour rendering calculation based on CAM02-UCS is reliable for the evaluating the colour rendering property of daylight simulators.

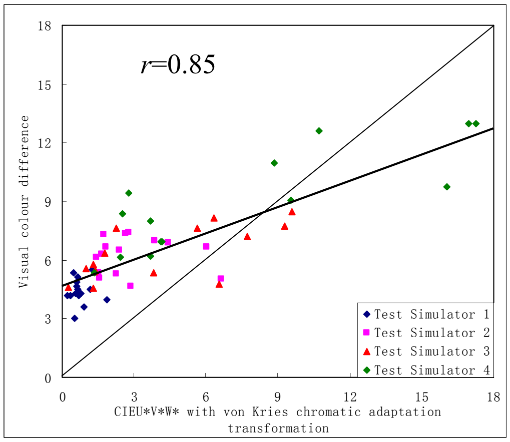

Figure 4 Visual colour differences against calculations based on U*V*W* colour space

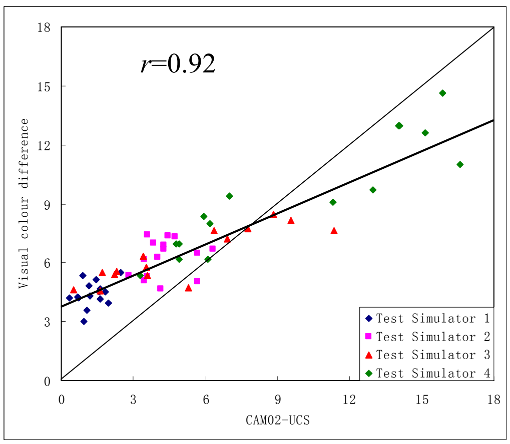

Figure 5 Visual colour differences against calculations based on CAM02-UCS

Furthermore, Sándor also found that the visually observed colour difference was not well described by the CIE test-colour method. In addition, he stated that the use of the CIECAM02 colour appearance model based colour difference formula can give better correlation to the visual results. Table 3 lists the correlation between the visual results and predictions for the 6500 K LED cluster with large colour differences used in Sándor's experiment and the test source 4 used in the present study.

		Colour Difference Formulae			
	R_a	CIE U*V*W*	CIELAB	CIE CAM02	CAM02 -UCS
LED cluster used in Sándor's experiment	50	0.84	0.86	0.89	not availabl e
Test source 4 used in the present study	52	0.86	0.86	0.91	0.91

Table3 The correlation between the visual results and predictions for the 6500 K LED cluster with large colour differences used in Sándor's experiment and the test source 4 used in the present study

It can be seen that both the LED cluster used in Sándor's experiment and the test source 4 used in the present study have R_a values of approximately 50, which indicates the similar colour rendering properties of these two light sources and large colour difference of test samples could be observed. Moreover, both the results show that the calculation method based on the CIECAM02 colour appearance model gives the best correlation to the visual results. In addition, the performances of different methods in terms of correlation coefficients are very similar in both experiments. For example, the correlation coefficients for the CIE test-colour method and CIECAM02 method are 0.84 and 0.89 respectively in Sándor's experiment, and they are 0.86 and 0.91 respectively in the present study. Although the correlation coefficient for CIECAM02 in Table 3 is only slightly better than that of the CIE test-colour method, the CV values in Table 2 are57 and 39 for using the CIE test-colour method and the CAM02-UCS method respectively, which indicates significant improvement by using the colour appearance model based colour difference formula. Most importantly, the same conclusions achieved by both experiments imply that the visual experimental method of using two viewing cabinets placed side by side to investigate the colour shifts of test samples is a solid and reliable method to visually assess the colour rendering properties of different light sources including the LED based light sources.

Conclusion

Visual experiment was carried out to investigate the performance of CIE colour rendering calculation method. The result shows that the colour difference calculation based on U*V*W* colour space and von Kries chromatic adaptation transformation can not predict the visual colour difference accurately. However, a modified calculation using CAM02-UCS can give better predictions. In addition, the visual experimental method of using two viewing cabinets placed side by side to investigate the colour shifts of test samples is a solid and reliable method to visually assess the colour rendering properties of different light sources.

References

[1] CIE TC1-62, 'Colour Rendering of White LED Light Sources', *CIE Technical Report*, 2006.

[2] M. R. Luo, G. Cui and C. J. Li, 'Uniform Colour Space Based on CIECAM02 Colour Appearance Model', *Color Research & Application*, Volume 31, Number 4, Aug 2006.

[3] CIE 13.3:1995, 'Method of measuring and specifying colour rendering properties of light sources', 1995.

[4] N. Moroney, M. D. Fairchild, R.W.G. Hunt, C Li, M. R. Luo and T. Newman, 'The CIECAM02 Color Appearance Model', *The tenth Color Imaging Conference, IS&T and SID*, Scottsdale, Arizona, 13-15 November, 2002 23-27.

[5] W. Davis, Y. Ohno, 'Toward an Improved Color Rendering Metric', *Proc. of SPIE* 5941: 59411G, 2005.

[6] C. Li, C. J. Li and M. R. Luo, 'Quality of LED Based Daylight Simulators', *CGIV2006*, Leeds, UK.

[7] W. G. Kuo and M. R. Luo, 'Methods for quantifying metamerism, Part 1-Visual assessment', *J.Soc.Dyers Col.*, 112,312-320, 1996.

[8] M. R. Luo, C. J. Li, R. W. G. Hunt, B. Rigg, and K. J. Smith, (2003) "CMC2002 colour inconstancy index: CMCCON02", *Coloration Technology* 119: 280-285

[9] N. Sándor and J. Schanda, 'Visual colour-rendering experiment', *Lighting Res. & Technol.*, 38/3 225-239 2006.
[10] M. D. Fairchild, and P. Lennie, (1992) "Chromatic adaptation to natural and incandescent illuminants", *Vision Research* 32: 2077-2085.

Author Biography

Cheng Li received his BS in optical engineering from the University of Zhejiang (2004) and is studying his PhD degree in the Department of Colour Science from University of Leeds. His work is focused on the LED based daylight simulator and colour rendering of light sources.

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