Recent Developments in Colour Rendering Indices and Their Impacts in Viewing Graphic Printed Materials

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Abstract

A new colour rendering index was developed. It has the following features: to use CAM02-UCS model including a robust chromatic adaptation transform and a uniform colour space, to apply 10^o observer to remove the anomalies of the 2^o observer in the close to blue area, to include 273 test samples to cover a large colour gamut corresponding to real world samples. It is a much improved CRI than the current CIE-R_a.

Introduction

This paper deal with one of the main activities of the CIE Division 1 (Vision and Colour): the development of a new colour rendering index, summarizing the ideas of two groups dealing with the subject: University of Leeds, UK and University of Pannonia, Hungary. The CIE colour rendering index is an important indicator of the colour quality of a lamp and has been widely used in industry, since it was first proposed in 1964, its latest update was in 1995 [1]. A workflow of the steps for calculating the CIE colour rendering index is given in Figure 1. The method calculates the resultant colour shifts for 14 test-colour samples (the spectral reflectance values of these samples are supplied). The resultant colour shifts are quantified by calculating the *CIE 1964 U*V*W** colour differences. For each test-colour sample illuminated under the test source and a reference illuminant with correction for chromatic adaptation, the calculated colour difference is then converted to an index, namely CIE special colour rendering index (R_i), *i* from 1 to 14, which were chosen from the Munsell Color Order system, covering the hue circle with moderate chroma and approximately equal lightness. The CIE general colour rendering index (R_a), which is the average of the special colour rendering indices for the first 8 test-colours, is defined to indicate the colour rendering property of a "white light" test light source. The other six test-colour samples, representing highly chromatic colours to approximate the size of colour gamut, and a complexion and a foliage colour to indicate the similarity of the memory colours, were added to this method to indicate the colour rendering properties of a test light source under extreme conditions.

There is a general consensus [2] that the current CIE R_a value is insufficient due to the use of obsolete CIE metrics: the *von Kries* chromatic adaptation transform and the *CIE 1964 U*V*W** colour space, and the relatively low saturation of the test samples. More importantly, some research results showed that it under-estimates the colour rendering capability of the newer LED light sources.

With this in mind, CIE Technical Committee (TC) 1-69 *Colour Rendition by White Light Sources* was formed with intention to recommend a new CRI. The Term of Reference is to investigate new methods for assessing the colour rendition properties of white-light sources used for illumination, including solid-state light sources, with the goal of recommending new assessment procedures. It has been a very active TC including work by 10 laboratories in 7 countries.

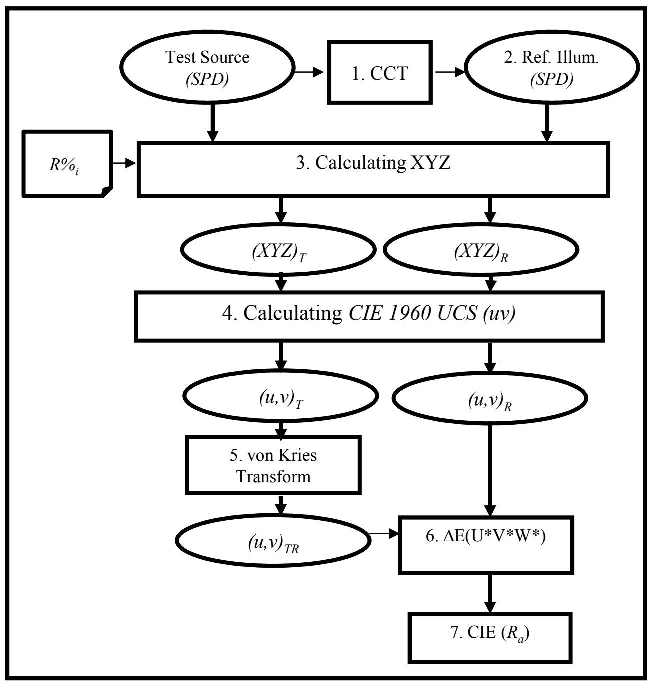


***Figure 1**. Workflow to calculate CIE R_a*

Many methods have been proposed by the TC members to update the existing CRI metric. One approach is based on the size of colour gamut [3], i.e. a source having a larger colour gamut can provide better colour discrimination or higher visual clarity. The gamut is defined in a suitable colour space using suitable test colours. Yaguchi *et al.* [4] also developed a categorical colour rendering index by applying a colour category technique to group colours into familiarised colour names under different illuminants. Errors in colour rendering will shift the categorical boundaries of the colour name regions. Another research group proposed a harmony colour rendering index [5]. A large distortion of colour harmony from the reference illuminant is considered to have a lower quality of colour rendering. Judd introduced his flattery index [6] and this has been recently revisited by Smet *et al.* [7], who developed the memory colour rendering index based on the similarity of the memory colour of familiar objects as reference to evaluate colour rendering.

Davis and Ohno [8] developed their colour quality scale (*CQS*). It assumes that a suitable (non-excess) increase of object chroma under the test source comparing with that under the reference illuminant is considered to be beneficial. The method will give an overall better rating for LEDs. Luo at Leeds [9] also proposed a method based on *CAM02-UCS*. This method is named *CRI-CAM02UCS* and Figure 2 shows the workflow of its calculations.

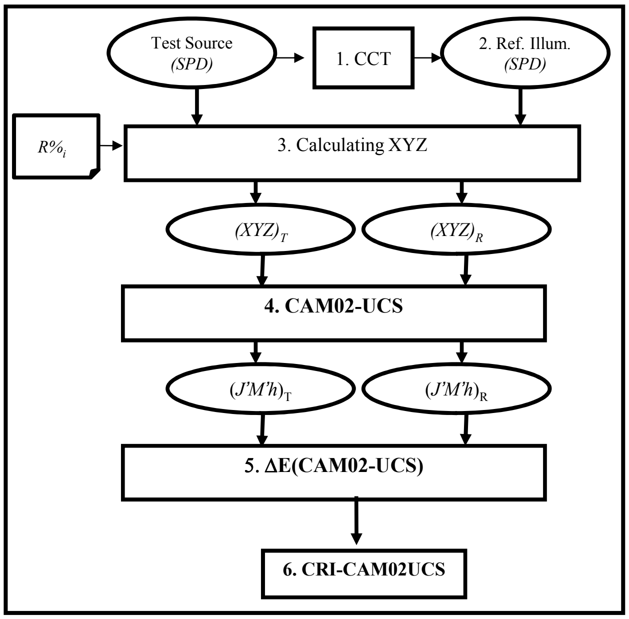


***Figure 2**. Workflow to calculate CRI-CAM02UCS*

Comparing Figures 1 and 2, *CRI-CAM02UCS* has one step less than *CIE-*R_a. This is because *CAM02-UCS* is not only a colour appearance model but also a uniform colour space, for which *CIE-*R_a includes two formulae: von-Kries chromatic adaptation transform and the *CIE 1964 (U*V*W*)* space. Both formulae were obsolete and do not accurately predict visual data.

The performance of the *CRI-CAM02UCS* was verified by different experiments [10-12] designed to assess colour differences between the reference and the test illuminant. The visual results were used to test different uniform colour spaces in terms of correlation coefficient. The results showed consistently *CAM02-UCS* significantly outperformed the others such as *CIEU*V*W**, *CIELUV*, etc.

The Revised CRI-CAM02UCS

Four attempts have been made to refine *CRI-CAM02UCS*. They are described below:-

1) The Test-sample set

The main refinement was focused on the test-samples involved. The initial work [13] involved the selection of 36 saturated samples from the Munsell Colour system for evaluating the colour rendering property of light sources. These had the lowest colour inconstancy value (CII) calculated based on CMCCON02 [14]. The value is reported in CIEDE2000 colour difference unit (ΔE_{00}) [15]. The reason to aim for high chroma colours is to improve the colour rendering rating for LED lamps.

It was later found that more samples are required in order to avoid the bias towards higher grade for LED lamps and to be able to optimise the performance of the lamps based on limited number of samples. This resulted in a new set of samples [16] and has the following characteristics:

- to include 219 samples evenly distributed in colour space having two C_{ab}* levels (20 and 50), three L* levels (30, 50 and 70) and hue angles at 10^o interval.
- to represent the world of real materials including 6 types: textiles, prints, photo, packaging inks, plastics, and skin, The samples were selected from the Leeds reflectance dataset including over 100,000 reflectance functions.
- to be highly colour constant having an average CII of 2.3 ΔE_{00}, and
- to cover a large colour gamut with a mean of 27 and a maximum of 53 C_{ab}* units at three lightness levels.

More recently, it was realised to be unnecessary to that many samples. For example, for samples having C_{ab}* of 50, neighbouring hue samples have an average ΔE_{ab}* about 7.0. However, for low chroma colours (C_{ab}* of 20), the difference is halved with the h_{ab} interval of 10^o which are too populated in a small region. Finally, a new set including 273 samples (90 colour constant, 90 colour inconstant and 90 reflectance difference samples plus 3 skin colours) were selected according to the following procedure:

(1) To select colour targets

The 90 target colours are plotted in CIELAB a*b* plane. The colours were selected from the earlier 219 data. The intention was to keep about the same colour gamut and to distribute evenly in colour space. Again, three L* levels (30, 50 and 70) were selected. Only colours having C_{ab}* of 20 were chosen for L* of 30 and 70. For L* of 50 plane, samples having C_{ab}* of 20 and 50 were used. For samples at C_{ab}* of 20 and 50, h_{ab} intervals of 20° and 10° were selected respectively. This gave 90 colours in colour space.

(2) To select samples close to targets

CIEDE2000 colour difference formula with 1931 standard colorimetric observer and CIE standard illuminant D65 was used to select colours close to the targets as found in Step 1) from the Leeds reflectance dataset. A tolerance of 2.5 ΔE_{00} units was used for each target.

(3) To select colour constant, colour inconstant, reflectance difference samples

The CII was used to select colour constant samples. The input value of the index is the reflectance of each sample found in the last step together with the tristimulus values of the reference source (CIE D65) and three test illuminants (A, F2 and F11). The output is the mean CII value of the three test illuminants in terms of ΔE_{00} expressing the degree of colour constancy. A zero colour difference indicates perfect colour constancy. For each target colour, the samples having the highest and lowest CII values were selected to form a metameric pair. Another set called "reflectance difference set" was selected [17]. This gives 270 samples in total. Three further samples were again used representing human complexion spectral reflectance. (Note that the term 'metameric set' is used here. However, they do not have zero colour difference as defined by the CIE under the reference illuminant (D65/10).)

An example is given below. Figure 3 shows the two reflectance spectra used for determining a target colour. Table 1 shows the colour rendering (R_i) values of these samples under 4 LED sources.

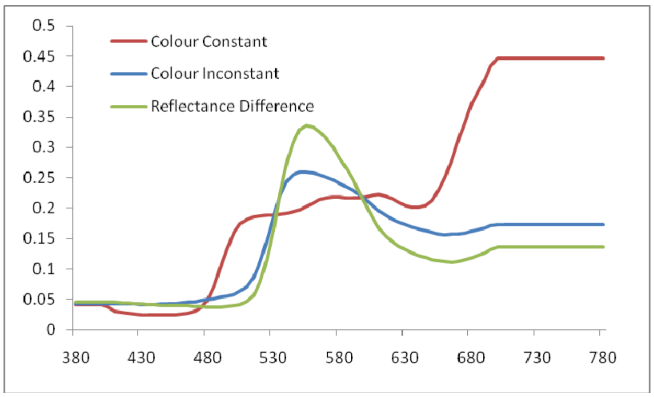
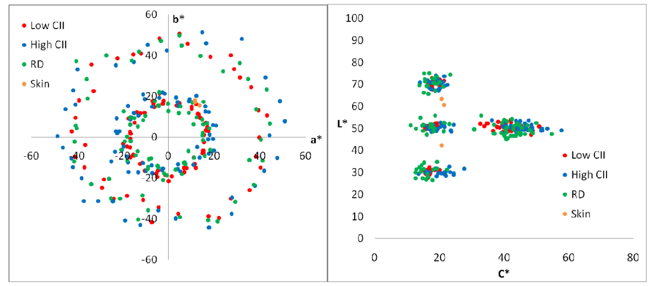


***Figure 3**. Reflectance spectra of three samples corresponding to a target colour.*

Table 1: The colour rendering values of some LED lamp spectra

Lamp	Colour constant	Colour inconstant	Reflectance Difference
RGB model (474/545/616)	88	80	63
4 peak 3012 K, Ra 70 desat 4	77	94	79
RGB model CRI optimized (Ra=90) -467/548/616	87	58	40
RGB LED-1	78	67	55

It can be seen in the table that the R_i values are quite different for each source, and a more colour constant sample may not give high R_i value all the time. Hence, a second set of colour inconsistent samples has been selected from the Leeds data-set, Finally, 273 data including 90 low CII, 90 high CII, 90 reflectance difference and 3 skin samples, where the colour constant samples were established here (best selection of the colour inconsistent samples will be published shortly). The samples were uniformly distributed on the CIELAB space in a*b* and L*C_{ab}* planes as shown in Figures 4(a) and 4(b) respectively.



(a) (b)

***Figure 4**. Colour distribution of the 273 set on (a) a*b* plane (b) L*C_{ab}* plane*

2) To avoid negative special colour rendering value

A general request was that the $\Delta E_i - R_i$ transformation should not obtain negative colour rendering indices. Thus root-mean-square (RMS) of CAM02-UCS colour differences and an exponential transformation as used also in the CQS [8] were applied:

$$E_{rms} = \sqrt{\frac{\sum_{i=1}^{N} \Delta E_i^2}{N}} \quad (1)$$

$$R_a = 10 \cdot \ln\left[\exp\left(\frac{100 - kE_{rms}}{10}\right) + 1\right] \quad (2)$$

3) Scaling factor based on a set of commonly used lamps

There is a need to ensure that on the average of the new CRI predictions agree with those of *CIE-*R_a for some commonly used conventional lamps. It was decided to ask main manufacturers to supply spectra of a number of light sources. Altogether, F1 to F12 were accumulated as major traditional lamps. For these light sources, the R_a values using the *CIE-*R_a was calculated. Using new sample set and the CIE 1964 10° observer for calculating colour-difference, [Note 10° observer was used here to avoid the error in the blue part of spectrum in 2° observer, which leads to misleading results for blue LEDs.]

The scaling factor (k) of the new (called nCRI) in Eq (2) for the new dataset is 7.16.

4) To calculate the special index min(R_i)

The individual R_i was calculated according to Eq (3). The minimum R_i from each dataset was defined as a special index.

$$R_i = 10 \cdot \ln\left[\exp\left(\frac{100 - k\Delta E_i}{10}\right) + 1\right] \quad (3)$$

Understanding the nCRI in graphic art applications

A set of 58 D50 simulators [18] was used here to represent the sources used in graphic arts industry. A set of typical CMY ink samples were generated including 349 samples, i.e. 7x7x7. Each sample's CII value (average under a D50 simulator and reference illuminant D65) was calculated. These were then averaged for that simulator. Note that an idea ink set should have a zero CII value to preserve the same appearance across all sources.) In addition, the CRI value for the four colour rendering formulae were used: CIE-R_a, CQS-CAM02UCS, CRI-CAM02UCS, and nCRI introduced here.

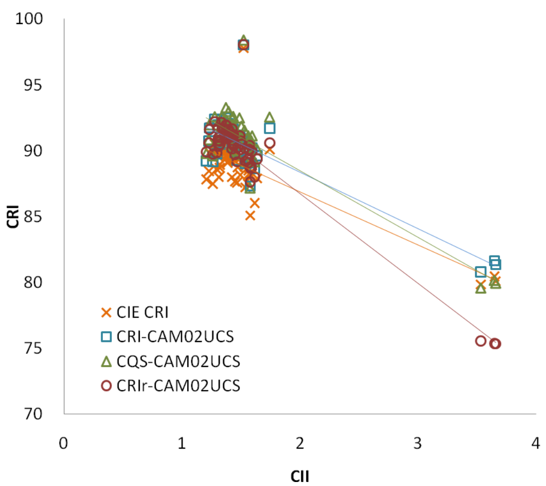


***Figure 5**. The CII values of CMY ink set plotted against CRI values calculated from 4 colour rendering indices for the 58 D50 simulators where CRIr-CAM02UCS is nCRI).*

The results in Figure 5 can be summarized below:-

- the mean CII for a typical CMY set is about 1.5 with a maximum of 3.7 among typical D50 simulators,
- a low colour constant sample (a high CII value) will result in a lower CRI for the lamps used. In the ISO 3664:2008, only simulators to have $R_a \geqq 90$ shall be used as D50 simulator. It can be seen that 60 % of the lamps are failed.
- Comparing 4 colour rendering formulae, it can be seen that nCRI had smaller value than the other formulae for the low CRI lamps.

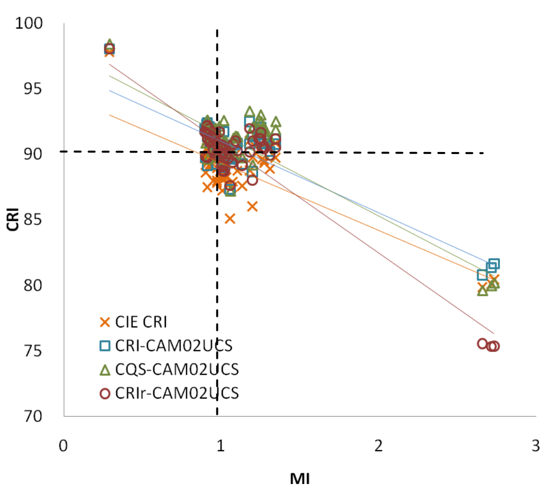


***Figure 6**. MI versus CRI for the D50 simulators accumulated where CRIr-CAM02UCS is nCRI). The two lines are the tolerances set by ISO3664.*

The next data analysis was carried out to compare the colour rendering index and metamerism index (MI) [19]. Only visible range was used. Both indices are recommended by ISO 3664. The MI considers the change of colour difference between the reference and test illuminants in terms of CIELAB colour difference. The CRI considers the change of colour appearance for a single patch between the reference and test illuminants. The ISO 3664 normative requirements are $R_a \geqq 90$ for CIE-CRI and MI-vis $\leqq 1.0\ \Delta E^*_{ab}$. It can be seen that only 20% can be accepted in the D50 simulator accumulated.

Conclusions

A new colour rendering index is introduced here. It includes a new test-sample set having 273 pairs (including 90 colour constant, 90 colour inconstant, 90 reflectance difference and 3 skin colours), which has uniform distribution, large colour gamut. The other refinements include to remove all negative colour rendering values, to use a standard set to calculate scaling factor and to use RMS rather than average ΔE for calculating colour rendering index. Finally, a typical CMY ink set was used to understand the characteristics between CII, CRI and MI-vis.

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