The Concept of Colour Rendering Revisited

János Schanda
Laboratory of Colour and Multimedia, University of Veszprém
Veszprém, Hungary

Abstract

The currently used colour rendering index is based on an outdated colour space and chromatic adaptation formula. The perceived and calculated colour rendering of new light sources shows discrepancies. This becomes acute with the introduction of LED sources and increased use of coloured samples produced by ink-jet printers and colour-photocopy. Recent colour appearance models enable an advanced description of colour rendering. The present paper shows some visual experimental results and draws attention on possible updates of colour rendering calculation.

Introduction

Since the introduction of the currently used colour rendering index (CRI) calculation[1] method, many new light sources have been introduced and new methods for colour appearance evaluation have been developed. As early as when the so called tri-band fluorescent lamps became available, based on an optimisation of luminous efficacy and the colour rendering index,[2] questions have been raised on the validity of the CIE method of calculating colour rendering (see e.g. Refs. 3, 4 and 5). In the mean time a number of new light sources, with different spectral power distributions became available, most recently those based on light emitting diodes (LEDs). It is anticipated that LEDs will be used in general practice interior lighting as well (several trials have already been carried out). Visual experiments show that the colour rendering impression and the calculated colour rendering indices do not correlate well for these sources.[6]

At the time, when the CRI calculation method was elaborated the most commonly used colorants have been pigments with broad absorption bands. At present many narrow band colorants are also in use, as e.g. coloured offset printing inks, inks used in desktop printers, etc. It is important for the imaging industry to know whether the every day illumination used for viewing the results of their work will render the pictures in the same way, as seen under their proof-lights, i.e. whether colour constancy holds for their products or not.

During the past years also the evaluation of chromatic adaptation and colour appearance has been improved considerably.[7] CIE itself tried several times to improve the recommendation of calculating the CRI, but without success,[8] probably mainly due to the fact that there was not enough experimental evidence available that would have justified a new colour rendering index calculation. In the present paper we intend to supply evidence of the weaknesses of the current method are, and discuss the experimental justification for possible advanced methods of CRI calculation.

Weaknesses of the Current CRI Calculation Method

The present CRI calculation method[1] uses the CIE U*V*W* colour space for all the calculations and a von Kries chromatic adaptation transformation between the test source and the reference source chromaticity. It is based on the colour differences calculated between the tristimulus values of some Munsell samples illuminated with the test and reference sources. The reference source is a Planckian or Daylight illuminant of the same correlated colour temperature as that of the test source, calculated in the u,v-diagram.

It is well known that the U*V*W* colour space is far from being equidistant, at the present moment we have a better approximation of an equidistant colour space in the form of the CIELAB space. But even this is not based on colour appearance studies, but on Munsell colour samples, i.e. on the evaluation of small colour differences. As an alternative one could experiment with a space based on a colour appearance model, should it be the CIECAM97s or one the CIE TC 8-01[9] is experimenting with Refs. 10 and 11, and 12. Based on better chromatic adaptation models (e.g. the Bradford transformation used in the CIECAM97s model[13]) one could transform both the test and reference source chromaticity to D65, where the equidistantness of the CIELAB space has been tested, or use a smaller number of reference sources, eventually an absolute method based entirely on D65 and CIELAB space.

For evaluating the colour difference there are also better ways now a days then the U*V*W* space (e.g. CIEDE2000[14]).

Finally the test samples used in the CIE CRI method are not available anymore in their material form, only metameric samples are to be obtained.[15] This makes it more difficult to reproduce visual experiments in the same form as done by the CIE committee some 30 years ago.[16]

Theoretical Considerations

The CIE defined colour rendering in the International Lighting Vocabulary[17] as:

"Effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant."

For practical use we have to translate this perceptual definition into a corresponding description based on colour stimuli, as only these can be accessed by measurement. The obvious choice therefore is to use instead of a colour space designed for colour difference calculation a colour appearance colour space. CIE TC 8-01 has not decided yet which colour appearance model it should choose for the description of colour appearance transformation among different media. The most thoroughly investigated comparison was the cathode ray tube monitor versus hard copy memory match comparison. Although this is not exactly the same situation as when one compares the colour appearance obtained by illuminating the same environment with two different light sources, but it comes close to it: one compares the colour appearance of test samples seen under a test source with those seen under a reference illuminant. Thus, based on the recent observations by Sueeprasan and co-workers[18] we decided to use the CIECAM97s model as our test model. (In this respect further investigations are under way, as at the recent meeting of CIE TC 1-27 the opinion was raised that the best model might depend on whether the scene seen is an interior or exterior scene.[19]) In colour rendering one has to compare scenes seen independently from each other, thus a memory match situation applies.

Experts seem to agree that the Bradford chromatic adaptation transformation[13,20] is better then the von Kries transformation[21] used in the original CIE test method.

The CIE definition says only "*comparison with their colour appearance under a reference illuminant",* but does not state the reference illuminant. The original idea was certainly to use a single reference illuminant and then the obvious choice would have been CIE D65, as most colorimetric experiments have been performed using D65 reference illuminant. In graphic arts a reference illuminant with lower correlated colour temperature is used,[22] because this enables the better bridging of low and high colour temperature regions. But this is a practical compromise and is certainly not based on theoretical considerations of best colour rendering. Van Trigt[23] has discussed the problem of reference illuminant from the point of view of colour constancy and concluded that CIE standard illuminant A does not have a perfect colour rendering, despite the fact that the present system of calculation assigns to every black-body radiator below 5000 K an Ra index of 100.

Fotios approached the problem in a recent paper[24] from an other point of view, investigating the apparent brightness provided by different illuminants. Fotios concludes that for equal CRI the lamp with higher correlated colour temperature (CCT) will provide a higher brightness appearance for the lit interior and vice versa, the brightness perception will be higher in an interior for the lamp of higher CRI if the two lamps have equal CCT. Brightness is, however, only one dimension of colour appearance space, thus the experiments reviewed in this paper can not give us full response how one should compare the colour appearance of a lit environment if the sources have different CCT.

Yaguchi and co-workers[25] proposed a colour rendering index based on categorical colour naming, i.e. whether an observed colour seen under the test source is falling into the same category as seen under a reference illuminant. For this they devised regions in CIECAM97s colour space, and tested samples lying at the border of such regions.

We are of the opinion that for colour rendering one needs a more continuous scale. It is not enough that we see blue as blue under a light source, but we have to provide information how much that blue colour has been distorted. Thus we suggest using something like a "colour difference" in a colour appearance space to describe colour rendering. To be able to build up such a model, we have first compared scales in the CIELAB and in the CIECAM97s spaces. While the CIELAB L^* scale is a cube-root function of Y, the J lightness scale of the CIECAM97s model can be approximated using an exponent between 0,4 and 0,5, depending on the luminance of the adapting white field. Figure 1 shows the L^* and J versus Y curves, in case of J for two adapting luminance levels (L_A). The $Y^{0,45}$ curve shows an approximation of the $J(Y)$ curve. There are many colour difference models (e.g. the Coloroid model[26]) that scale the lightness as a square root function. Thus this difference can be regarded as negligible.

Chroma and hue-angle coordinates differ more in CIELAB and CIECAM97s spaces. Figure 2 shows for $Y = 50$ the lines that correspond to horizontal, vertical and 45° inclined a^*,b^* lines.

Experiments are under way to test and compare scales built using the two spaces.

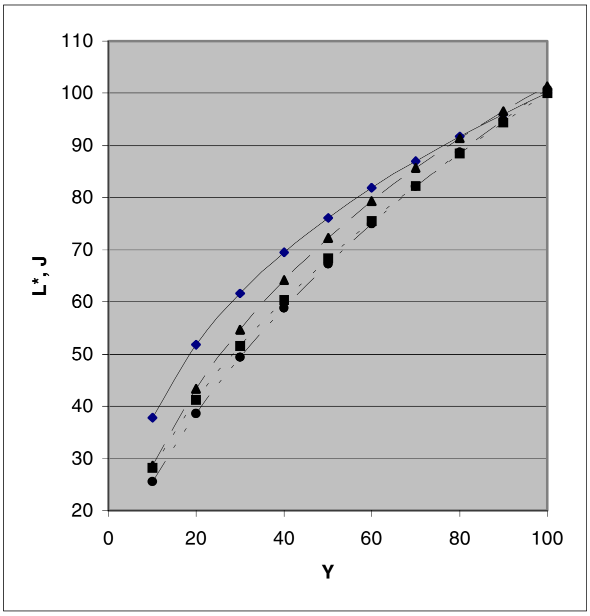

Figure 1. Metric lightness scales in CIELAB space (—♦—), in CIECAM97s space (L_A=10: — -- —●—, L_A=333: —▲— —) and the $Y^{0,45}$ function (- -■ - - -).

Visual Experiments

A double booth experiment was set up to compare the visual appearance of test samples illuminated by a test and a reference light source. Mainly Macbeth ColorChecker Charts[27] were used as test samples, as the last CIE effort to establish a new CRI calculation method recommended some of the samples of this chart too, and the charts are readily available and much used in photographic colour evaluation work. Some preliminary experiments were conducted also using metamers of the ColorChecker samples prepared with different techniques: Textile samples, ink-jet and colour laser-printer print-outs.

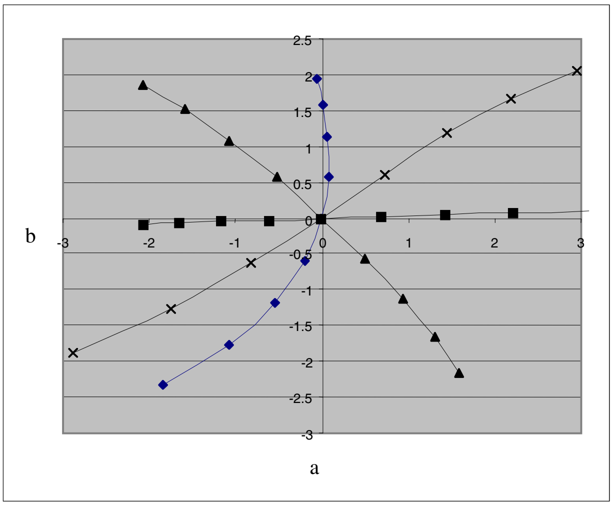

Figure 2. CIECAM97s a, b coordinates for Y=50, for horizontal, vertical and 45° inclined a, b* lines*

We conducted experiments using the following sources:

- A filtered incandescent D65 simulator with a visible Category A evaluation according to the CIE method of assessing the quality of daylight simulators.[22] This will be called in the following the "*reference source*".

The other sources used in the experiment are termed the *test sources*:

- Compact fluorescent lamps of average good colour rendering (using tri-band type phosphors).
- Two clusters of "white LEDs": blue LEDs with built in phosphors having a near white colour appearance, but of different CCT.
- Two clusters of red, green and blue LEDs, where the emission of the LEDs was set to get a near D65 chromaticity, and also some further CCT values, to be able to compare their CRI with that of the different compact fluorescent lamps of different CCT.

In the first experiment – to be discussed at this meeting – all sources had near D65 chromaticity, so that the abridgment of large chromatic differences was not necessary. Further experiments are under way to evaluate also low colour temperature light sources. The filtered incandescent lamp and the fluorescent lamps had high light output, with these a generally recommended 1000 lx – 2000 lx illumination on the sample surface could be obtained. However we dimmed these sources so that the sample area illuminance was set to 250 lx. According to our pilot experiments this was high enough to have good colour discrimination. This was necessary because with the LED clusters we could not achieve higher illuminance and wanted to have the illuminance level for all the sources comparable.

The task of the observer was to compare the colour appearance of the test samples seen in the booth illuminated by one of the test sources with the samples seen in the other booth illuminated by the reference source. In the reference chamber also two grey samples were placed for anchoring the colour appearance scale. The observer was asked to tell how different the test samples appeared to him or her compared to the colour difference of the two grey samples. Observers could see only the samples in one of the chambers at a time, but were permitted to look at one chamber or the other repeatedly before they signalled their evaluation to the person who conducted the investigation. Above experiment was repeated with all the test sources. A few tests were conducted also by reversing the placement of the test and reference sources to test the symmetry of the arrangement. No significant asymmetry was found.

Three observers were experienced in colour appearance evaluation, five university students had not much prior knowledge of colour appearance scaling. Their colour vision, tested with Ishihara plates was normal. They got a detailed introduction, their attention was directed to colour differences observed under different conditions, and they were not limited in time to perform the investigation.

Physical Measurements and Evaluations

The spectral power distribution of the reference and test lamps has been measured using an array spectroradiometer. For the narrow band LED sources this measurement was repeated and corrected using a double monochromator spectroradiometer, as experiments showed that for narrow band emitters one has to calculate with a higher uncertainty in case of an array type spectroradiometer due to the higher stray light of these systems.[28]

The 0°/45° reflectance factor of the test samples has been determined using an automatic spectrophotometer.

Using above data the tristimulus values for all the samples under all the light sources have been calculated using the CIE 1931 standard observer. Colour differences have been calculated between the corresponding samples seen under the reference source and the test sources. Due to the fact that for most sources the colour differences were relatively large ($\Delta E_{ab} > 5$), we have used the CIELAB formula and not the CIEDE2000 equation. (Tests are under way to evaluate the difference.) As an alternative the CIECAM97s coordinates have been calculated also and coordinate differences evaluated. For these calculations 250 lx illumination and average background have been used (see the Section on Visual experiments).

Evaluation

The colour differences based on the physical measurements have been compared with the results of the visual experiments. Figure 3 shows as an example of the correlation between the visual assessment and the Ra value based on the CIE test method.

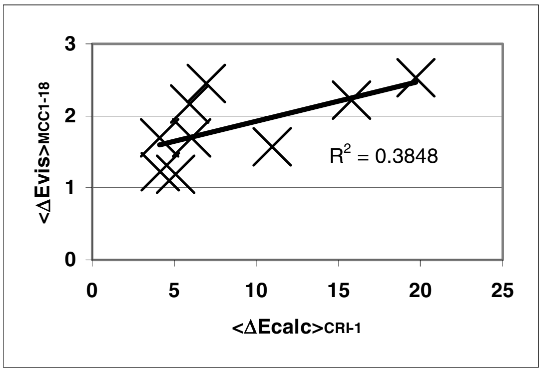

Figure 3. Correlation between some visual observations and the Ra value

As can be seen from the figure the correlation is rather poor. For the imaging industry it is important to know how well different techniques reproduce colours. Thus we experimented also with different sample sets. Table 1 shows colour rendering indices for four LED sources using the traditional CIE method of colour rendering calculation, and two sets of other test samples: the Macbeth ColorChecker Chart and a metameric sample set based on printing inks, kindly supplied by the EMPA institution. For comparison we have included also the CIE Fluorescent Lamp FL 4,[29] a Warm White lamp with halophosphate phosphor that served as the reference at the time of establishing the CIE test method. The fluorescent lamp has a very different correlated colour temperature then the LED clusters, thus it is not ideal for comparison, but shows clearly how important the selection of the test samples is – or whether one should try to find a method not based on physical samples.

Table 1. Correlated colour temperature (TCC), chromaticity distance from Daylight locus (dC) and Ra values using different sets of test samples.

	TCC	dC	Ra/13.3	Ra/Col.Ch	Ra/EMPA
Blue+Ph 1	8372	7.10^{-3}	83	76	82
Blue+Ph 2	7566	$3{,}6.10^{-2}$	78	67	73
RGB1	7246	$3{,}6.10^{-2}$	51	3,2	16
RGB2	7168	$1{,}8.10^{-2}$	64	20	31
CIE FL4	2938	$8{,}2.10^{-4}$	51	9	19

Two of the four LED clusters were blue LEDs with phosphors, two other ones where clusters composed from red, green and blue LEDs. The chromaticity of none of the LED sources was near enough to the Daylight Locus for meaningful CRI calculation, according to CIE 13.3. This is shown by the relatively large dC value. The broadband blue+phosphor emitting LEDs provide a not too bad general colour rendering index, Ra. The three band LEDs (produced by adding to the cluster red, green and blue emitting diodes), have a poor CIE colour rendering index, and partly extremely low values for the alternative samples. This shows clearly that we will have to deal with this question in more detail, testing further inks and pigments.

Conclusion

Although we still do not have a perfect description of colour rendering, we can do much better then the CIE method can do. An important aspect is that beside the classical broadband reflectance spectra of traditional paints and varnishes, the use of modern reproduction techniques provides us with metameric samples. A colour rendering index should take also these alternative reflectance spectra into consideration. This becomes very important if narrow band emission spectra are used as illuminants. The compact fluorescent lamp phosphors have been designed to get high colour rendering index, and not good visual colour rendering. One should not repeat this error now, when the LED sources are developed. One could certainly tailor the semi-conducting materials to get high CRI, but these will not necessarily (based on our experiments we can say will not) look pleasing and provide good colour rendering. We hope that our experimental findings will lead to a new and better calculation method of the colour rendering index.

References

1. Commission Internationale de l'Eclairage: Method of measuring and specifying colour rendering properties of light sources. Publ. CIE 13.3-1995 (a verbatim re-publication of the 1974 2nd edition).
2. Verstegen J; Radielovic D; Vrenken L E, A new generation of "deluxe" fluorescent lamps combining an efficacy of 80 lumens/w or more with a color rendering index of approximately 85. A Survey of Phosphors, 121, No. 12, 1627-1631.
3. Schanda J, Colour rendering and the impression of comfort with artificial illumination. Information Couleur, 3/2, 23-28, 1978.
4. Valberg A; Thorstein S; Sällström P, Colour rendering and the three-band fluorescent lamp. Annex 6 to Circular 2/80, Mtg of the CIE 1979, Kyoto.
5. Pointer MR, Measuring colour rendering - a new approach. Lighting Res. & Techn. 18/4, 175-184, 1986.
6. Tarczali T, Bodrogi P, Schanda J, Colour rendering properties of LED sources. CIE Expert Symposium on LED measurement standard methods for specifying and measuring LED and LED cluster characteristics, Gaithersburg, 2001.
7. Commission Internationale de l'Eclairage: The CIE 1997 interim colour appearance model (simple version) CIECAM97s. Publ. CIE 131-1998.
8. Commission Internationale de l'Eclairage: Colour rendering, TC 1-33 closing remarks. Publ. CIE 135/2 1999.
9. Commission Internationale de l'Eclairage: Colour appearance modeling for colour management applications. CIE TC 8-01.
10. Luo MR: The LLAB model for colour appearance and colour difference evaluation, Recent Progress in Colour Science, IS&T, Springfield, VA., 158-164. 1997.
11. Li C, Luo M: A uniform colour space based upon CIECAM97s. AIC 2001 Conference, Rochester 2001.

12. Fairchild MD, A revision of CIECAM97s for practical applications. COLOR Res & Appl. 26/6 418-427 2001.
13. Lam KM: Metamerism and colour constancy, PhD Thesis, Univ. of Bradford, 1985.
14. Commission Internationale de l'Eclairage: Improvement to industrial colour difference evaluation. Publ. CIE 141-2001.
15. Witt K: The Bundesanstalt für Materialprüfung (BAM) produces such metameric test samples, private communication.
16. Nickerson D; Jerome C W: Color rendering of light sources: CIE method of specification and its application. Illum. Eng. 262-271, April 1965.
17. Commission Internationale de l'Eclairage: International Lighting Vocabulary. Publ. CIE 17.4-1987.
18. Sueeprasan S, Luo MR, Rhodes PA, Investigation of colour appearance models for illumination changes across media. COLOR Res & Appl. 26/6 428-435 2001.
19. CIE TC 1-27 meeting, Rochester, 2001.
20. Luo MR, Hunt RGW, A chromatic adaptation transformation and a colour inconsistency index. COLOR Res & Appl. 23 154-158 1998.
21. Von Kries J, Die Gesichtsempfindungen, Nagel's Handbuch der Physiologie des Menschen 3 211 1904.
22. Commission Internationale de l'Eclairage: A method for assessing the quality of daylight simulators for colorimetry. Publ. CIE 51.2-1999.
23. Van Trigt C, Color rendering, a reassessment. COLOR Res & Appl. 24/3 197-206 1999.
24. Fotios SA, Lamp colour properties and apparent brightness: a review, Lighting Res. Technol. 33/3 163-181 2001.
25. Yaguchi H, Takahashi Y, Shioiri S, A proposal of color rendering index based on categorical color names. Internat. Lighting Congress, Istanbul 2001.
26. Nemcsics A, Color space of the Coloroid color system. COLOR Res & Appl. 12/3 135-146 1987.
27. McCamy CS, Marcus H, Davidson JG: A color-rendition chart. Jr. Photographic Engng. 2/3, 95-99, 1976.
28. Muray K, Kranicz B, Ohno Y, Schanda J: Comparison measurements of LED spectral power distribution. CIE Expert Symposium on LED measurement standard methods for specifying and measuring LED and LED cluster characteristics, Gaithersburg, 2001.
29. Commission Internationale de l'Eclairage: Colorimetry. Publ. CIE 15.2-1986.

Biography

János Schanda received his B.S. and M.S. degrees in Physics at the Loránd Eötvös University in Budapest, Hungary. He received his PhD degree at the Technical University in Budapest.

After a short period at the Hungarian Office for Measures he spent most of his active life at the Research Institute for Technical Physics of the Hungarian Academy of Sciences, where he was responsible for the Department for Optics and Electronics.

He was in charge of the Central Bureau of the CIE for ten years, and since 1995 he is at the University of Veszprém where he was head of the Department for Image Processing and Neurocomputing. Currently he is leading the Laboratory of Colour and Multimedia at the Univeristy of Veszprém.

He is Secretary of the CIE and chairs several Technical Committees of the CIE. He is the president of CIE-Hungary and the Technical Committee of Applied Light and Colour Technologies of the Veszprém Branch of the Hungarian Academy of Sciences, and is a member – beside of several Hungarian societies – of the IS&T and the Optical Society of America. E-mail address: schanda@ella.hu