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CIE

COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL
REPORT

COLOUR RENDERING OF WHITE LED LIGHT SOURCES

CIE 177:2007

UDC:	628.938 628.981	Descriptor:	Influence of the colour of the light Evaluation of light sources

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3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
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2. Grundnormen und Verfahren der Meßtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
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Descriptor: Influence of the colour of the light
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This Technical Report has been prepared by CIE Technical Committee 1-62 of Division 1 "Vision and Colour" and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

Ce rapport technique a été élaboré par le Comité Technique CIE 1-62 de la Division 1 "Vision et Couleur" et a été approuvé par le Bureau de la Commission Internationale de l'Eclairage, pour étude et emploi. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire. Il faut consulter les plus récents comptes rendus de la CIE, ou le CIE NEWS, en ce qui concerne des amendements nouveaux éventuels.

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The following members of TC 1-62, "Colour rendering of white LED light sources" took part in the preparation of this technical report. The committee comes under Division 1 "Vision and Colour".

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COLOUR RENDERING OF WHITE LED LIGHT SOURCES

SUMMARY

This Technical Report reviews the applicability of the CIE colour rendering index to white LED light sources based on the results of visual experiments. The currently recommended colour rendering index (CRI) calculation method was officially introduced in 1974, and is described in the current publication CIE 13.3-1995 (CIE, 1995). Visual experience has shown that the current CRI based ranking of a set of light sources containing white LED light sources contradicts the visual ranking.

In this Technical Report, three recent visual experiments (including simulations) on colour rendering including white LED light sources are described that confirm this contradiction. It was concluded from these visual colour rendering results that the current CRI method did not describe well those situations where white LED light sources were involved i.e. if white LED light sources were visually ranked together with other light sources. Low correlation was found between the visual colour differences and the computed colour differences if the current CRI method was applied to calculate those colour differences. The conclusion of the Technical Committee is that the CIE CRI is generally not applicable to predict the colour rendering rank order of a set of light sources when white LED light sources are involved in this set.

The Committee recommends the development of a new colour rendering index (or a *set* of new colour rendering indices) by a Division 1 Technical Committee. This index (or these indices) shall not replace the current CIE colour rendering index immediately. The usage of the new index or indices should provide information supplementary to the current CIE CRI, and replacement of CRI will be considered after successful integration of the new index. The new supplementary colour rendering index (or set of supplementary colour rendering indices) should be applicable to all types of light sources and not only to white LED light sources. Possibilities for an improved description of colour rendering are summarized in the Appendix of this Technical Report.

RENDITION DE LA COULEUR DES SOURCES DE LUMIERE LED BLANCHES

RESUME

Ce rapport technique examine la validité de l'indice de rendu des couleurs CIE pour les sources lumineuses blanches à base de diodes électroluminescentes (DEL) à partir des résultats d’expériences visuelles. La méthode actuellement recommandée pour le calcul de l'indice de rendu des couleurs (IRC) a été officiellement introduite en 1974, elle est décrite dans la publication CIE 13.3-1995 (CIE, 1995). L’expérience visuelle a montré que, pour un ensemble de sources lumineuses contenant les sources lumineuses blanches à base de DEL, le classement fondé sur l’IRC actuel contredit le classement visuel.

Dans ce rapport technique, on décrit trois expérimentations visuelles récentes (simulations comprises) qui confirment cette contradiction sur le rendu des couleurs, avec des sources lumineuses blanches à base de DEL. En conclusion de ces résultats sur le rendu visuel des couleurs, la méthode actuelle de calcul de l’IRC n'a pas bien décrit les situations où les sources lumineuses blanches à base de DEL étaient impliquées, c.-à-d. quand des sources lumineuses blanches à base de DEL étaient classées visuellement avec d'autres sources lumineuses. On a trouvé une faible corrélation entre les différences de couleur visuelles et les différences de couleur calculées quand la méthode actuelle du calcul de l’IRC était appliquée. Le Comité technique conclut que l’IRC CIE n'est généralement pas applicable pour prévoir le classement du rendu des couleurs d'un ensemble de sources lumineuses quand des sources lumineuses blanches à base de DEL font partie de cet ensemble.

Le Comité recommande le développement d'un nouvel indice de rendu des couleurs (ou d'un ensemble de nouveaux indices de rendu des couleurs) par un Comité technique de la Division 1. Cet indice (ou ces indices) ne remplacera pas l'actuel indice de rendu des couleurs CIE immédiatement. L'utilisation du nouvel indice ou des nouveaux indices devrait fournir des informations complémentaires à l’actuel IRC CIE, et le remplacement de l’IRC actuel sera envisagé après l'intégration satisfaisante du nouvel indice. Le nouvel indice supplémentaire de rendu des couleurs (ou l'ensemble d'indices supplémentaires de rendu des couleurs) devrait être applicable à tous les types de sources lumineuses et non seulement aux sources lumineuses blanches à base de DEL. Des possibilités de description améliorée du rendu des couleurs sont récapitulées dans l'annexe de ce rapport technique.

FARBWIEDERGABE WEISSER LED LICHTQUELLEN

ZUSAMMENFASSUNG

Dieser technische Bericht überprüft, basierend auf den Ergebnissen von visuellen Versuchen, die Anwendbarkeit des CIE Farbwiedergabeindex auf weiße LED Lichtquellen. Die derzeit empfohlene Berechnungsmethode für den Farbwiedergabeindex (CRI) wurde 1974 offiziell eingeführt und ist in der gegenwärtigen Veröffentlichung CIE 13.3-1995 (CIE, 1995) beschrieben. Visuelle Erfahrungen haben gezeigt, dass die gegenwärtige, auf CRI basierende Bewertung einer Reihe von Lichtquellen, die weiße LEDs enthalten, der visuellen Rangfolge widerspricht.

In diesem technischen Bericht werden drei neue visuelle Versuchsreihen (einschließlich Simulationen) zur Ermittlung der Farbwiedergabe auch weißer LEDs beschrieben, die diesen Widerspruch bestätigen. Aus den Ergebnissen dieser visuellen Farbwiedergabeversuche wurde geschlossen, dass die gegenwärtige CRI-Methode Beleuchtungssituationen mit weißen LED Lichtquellen nicht gut beschreibt, d.h. solche Fälle, in denen weiße LED’s visuell zusammen mit anderen Lichtquellen eingeordnet werden. Zwischen den visuellen Farbunterschieden und den berechneten Farbunterschieden wurde nur eine schwache Korrelation gefunden, wenn die gegenwärtige CRI-Methode zur Berechnung der Farbunterschiede angewandt wurde. Die Schlussfolgerung des Technischen Komitees ist, dass die CRI-Methode generell nicht anwendbar ist, um eine Anzahl von Lichtquellen gemäß ihrer Farbwiedergabe einzuordnen, wenn weiße LEDs darunter sind.

Das Komitee empfiehlt die Entwicklung eines neuen Farbwiedergabeindex (oder eines Satzes von neuen Farbwiedergabeindizes) durch ein Technisches Komitee der Division 1. Dieser Index (oder diese Indizes) sollen den gegenwärtigen CIE Farbwiedergabeindex nicht sofort ersetzen. Der Gebrauch des neuen Index oder der neuen Indizes sollte Informationen liefern, die den gegenwärtigen CIE CRI ergänzen. Ein Ersatz des CRI wird erst nach erfolgreicher Integration des neuen Index in Betracht gezogen. Der neue zusätzliche Farbwiedergabeindex (oder Satz von zusätzlichen Farbwiedergabeindizes) sollte auf alle Arten von Lichtquellen anwendbar sein und nicht nur auf weiße LEDs. Die Möglichkeiten für eine verbesserte Beschreibung der Farbwiedergabe sind im Anhang dieses technischen Berichts zusammengefasst.

1. INTRODUCTION

Colour rendering (CR) 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" (CIE, 1987). The currently recommended colour rendering index (CRI) calculation method was officially introduced in 1974, and it is described in the current publication CIE 13.3-1995 (CIE, 1995). CIE first standardized a spectral band method (1948), but in 1961, it was decided to regard the "test sample colour shift" method (CIE, 1995) as the fundamental method for CR appraisal.

Besides graphical colour shift vector representations and multi-number rating, it seemed desirable to derive a *single-number* CR characterization of each light source. Later demand resulted in the establishment of the current CIE CRI calculation method. It may be of interest to mention that, besides the concept of CR, there exist other concepts to describe light source "colour quality" (Halstead, 1977; Valberg et al., 1980) (CQ), including colour discrimination capability (Thornton, 1973; Schanda and Czibula, 1980), "visual clarity" (Hashimoto and Nayatani, 1994), and colour preference or "flattery" (Judd, 1967).

There are several types of white LED light sources, including the so-called *clusters* of red, green, and blue (RGB) LEDs (including eventually other colours e.g. amber or yellow in the cluster or in one chip), white phosphor LEDs, and organic white LEDs. Fig. 1 shows the relative spectral power distributions of a typical RGB LED cluster and a white phosphor LED.

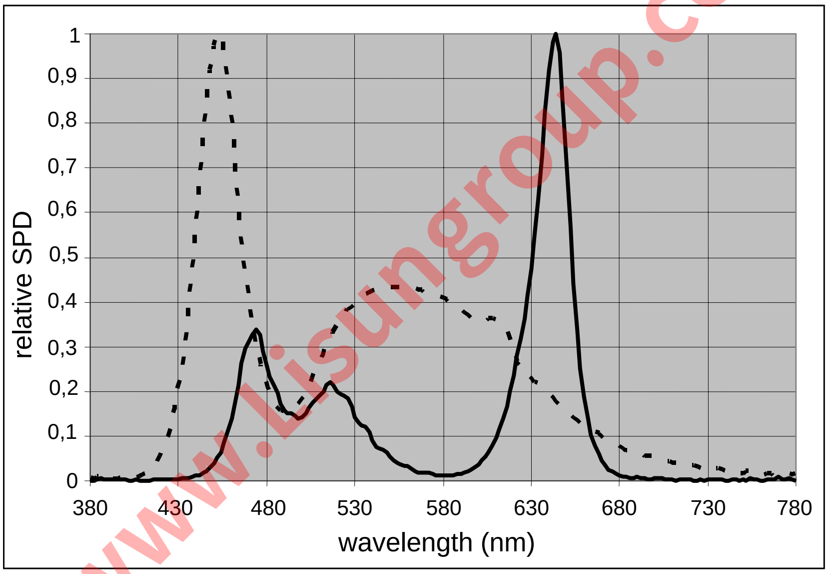

Fig. 1. Relative spectral power distributions of a typical RGB LED cluster (solid line) and a white phosphor LED (dashed line).

White LED light sources are efficient, long-living, and compact. The luminous flux and luminous efficiency of commercially available white LED light sources is rapidly improving. Today, by varying the types of LEDs used in the LED light sources, high CIE colour rendering indices (up to 97-99) could be achieved.

But visual experience shows that the CIE colour rendering index based ranking of a set of light sources containing white LED light sources by the current CIE colour rendering index (CIE, 1995) often contradicts the visual ranking (Sándor et al., 2003; Sándor et al., 2004; Bodrogi et al., 2004; Szabó, Sándor et al., 2005; Sándor and Schanda, 2005; CIE, 2002). Although, since the introduction of the CIE CRI calculation method in 1974, several *shortcomings* of the method have been realized and a number of new colorimetric recommendations [CIELAB and CIELUV colour spaces, new chromatic adaptation transforms and the CIECAM02 (CIE, 2004a) colour appearance model] have been made (Schanda, 2002; Bodrogi, 2004), today the CIE Colour rendering index (CIE, 1995) (using an outdated colour space and an outdated colour discrimination formula) is still the only officially endorsed numerical method to describe the colour rendering properties of any light source.

Recently, several visual experiments have been carried out on the colour rendering of white LED light sources partially in the framework of this Technical Committee. Visual experiments comparing white LEDs and non-LED light sources, as well as simulations have been performed. A summary of these studies is given in Section 2.

Concerning the applicability of the CIE colour rendering index to white LEDs (Section 3), the general conclusion of the studies described in Section 2 was that the visual results showed insufficient correlation with the CIE CRI predictions. This Technical Report states that the applicability of the current CIE colour rendering index (CIE, 1995) is limited if applied to white LED light sources.

To overcome this difficulty, the future development of a new index is recommended, to *supplement* (and eventually replace) the current CIE colour rendering index (Section 4). Possibilities to improve the CIE colour rendering index are proposed in the Appendix.

2. VISUAL EXPERIMENTS AND SIMULATIONS ON COLOUR RENDERING

2.1 A colour rendering simulator at the Hiroshima City University (Japan)

In this study (Nakano et al., 2005), a multispectral camera was used to estimate the spectral reflectance of natural scenes pixel by pixel, and then the tristimulus values of the scene under a certain illuminant were reproduced on a calibrated CRT monitor. This technique was applied to visually evaluate the colour rendering properties of white LED light sources including nine RGB LED clusters and one blue LED with a yellow phosphor. The semantic differential method was applied (consisting of 18 adjective pairs like high fidelity-low fidelity, warm-cool, saturated-desaturated, beautiful-ugly, and similar pairs) to evaluate the visual impression of 5 natural scenes under these illuminants. Principle component analysis of the results showed two relevant factors. The first factor (70%) was associated with the visual impression of colourfulness, and the second factor (16%) with colour fidelity. The second factor correlated well with the CIE colour rendering index (R_a) but the correlation of the first factor was found to be low. Authors concluded that a new colour rendering index was needed to fully describe the visual impression related to the colour rendering phenomenon.

2.2 Colour rendering simulations at the National Institute of Standards and Technology (NIST, USA)

NIST has been performing a series of colorimetric simulations, examining the appearance of many different reflective samples when illuminated by various light spectra. The sources tested include about 40 different existing lamps, about 30 LED models (RGB, RGBY, phosphor), and five theoretical spectra. The output of the CRI has been compared with visual observations from these simulations (Ohno, 2004; Davis, Gardner and Ohno, 2005; Ohno, 2005) as well as by numerically assessing the colour shifts (magnitude and direction) of samples on CIELAB coordinates. These analyses showed several problems with assessing LED sources with the CRI. It was observed that several RGB LED models render the reflective samples used in the calculation of R_a well, and achieve high scores, but render samples of higher chroma poorly. Further, the peaked spectra of LED models are particularly vulnerable to poor rendering of just a small range of hues, and the eight samples give insufficient coverage of all the possible hues. In some instances, RGB LEDs produce only one or two colour samples with large (unacceptable) colour differences, while all other colours show very small colour differences. In this case, the CRI score remains high. This indicates a problem in simple averaging of colour differences. Because of near limitless ways that individual narrowband LEDs can be combined to create white light, two other aspects of the CRI have the potential to be problematic. The matching of the reference source's CCT (Correlated Colour Temperature) to that of the test source assumes perfect chromatic adaptation, which fails at extreme CCTs (i.e. CCTs higher than 12000K or lower than 1500K). Finally, some RGB LEDs increase the chroma of objects, which is considered a possible important feature of LED lighting but is penalized by the CRI. Commercially, increases in chroma are considered a desirable trait in a lamp (Hashimoto and Nayatani, 1994), as evidenced by the success of the neodymium lamp. Based on these observations, the authors have proposed several modifications of the CRI, to overcome its shortcomings in assessing LEDs (Davis and Ohno, 2005). Their proposed metric, called the Color Quality Scale (CQS) uses 15 high-chroma reflective Munsell samples and calculates colour differences in CIELAB space. To account for large colour shifts even in small number samples properly, the colour differences are combined via root-mean-square rather than averaging. A "Saturation Factor" is implemented, such that lamps are not penalized for increases in object chroma [see also (Schanda, 1985) for a similar proposal]. Other changes include the implementation of a "CCT Factor", which penalizes lamps with extreme CCTs, a scaling factor that makes CQS scores comparable to R_a for traditional lamps, and a conversion to a 0-100 scale to eliminate negative outputs. Further computational work is underway and will include implementing CMCCAT2000 to account for chromatic adaptation. At this point, only numerical analyses and visual observation of simulated appearance of colour samples have guided this work. Systematic visual experiments will be critical to confirm the validity of these suggestions and such experiments using real light sources are being prepared at NIST.

2.3 Visual colour rendering experiments at the University of Pannonia (Veszprém, Hungary)

In this study (Sándor and Schanda, 2005), a series of visual colour rendering investigations were described and their correlation with the current CIE method (CIE, 1995) of calculating the colour rendering index, as well as with possible updates of this calculation method, were evaluated. The CIE method calls for a direct comparison of samples illuminated by the test source and a reference source, and the determination of the colour difference observed for each sample illuminated by the two sources. Therefore, in this experimental study, a double booth was constructed, where in one booth, a reference lamp illuminated the samples and in the other booth different test light sources were installed. An opal diffuser was placed between the lamp-compartment and the test chambers producing an even illuminance at the bottom of the compartments. The walls and the bottom of both compartments were painted with a medium grey matte paint.

The visual experiments were conducted by using lamps of three CCT levels, corresponding to Warm White, Cool White and Daylight lamp colours. For each CCT level, one lamp with a good CIE colour rendering index was selected as reference and the other lamps as test sources, to be able to check visual colour rendering compared to the value of the CIE colour rendering method. The task of the observer was to scale the visual colour difference between the corresponding chromatic samples of the MacBeth ColorChecker Charts (MCCs). To aid the observer, a grey scale was placed in the reference compartment, so that the observer could estimate the observed colour difference by comparing it to a given lightness difference of the grey scale. Observers were permitted to look into one or the other booth several times before they made their judgment. The chromaticity difference between the test and reference lamps was low, thus the chromatic re-adaptation was negligible.

The visual experiments of this study (Sándor and Schanda, 2005) showed that, for white phosphor LED light sources, correlation coefficients between visual colour differences and the CIE method predictions ranged between -0,62 and 0,50 and these correlation coefficients were not significant. For RGB LED clusters, these correlation coefficients ranged between 0,75 and 0,82 and they were significant. Another calculation method based on calculating colour differences using the CIECAM02 colour appearance model provided better correlation between the visual and the calculated colour rendering scales, with correlation coefficients ranging between 0,04 and 0,47 for white phosphor LED light sources and between 0,73 and 0,89 for RGB LED clusters. It was concluded that the current CIE method was not a good predictor of the visual perception of colour rendering and that even a more fundamental re-thinking of the concept of colour rendering would be appropriate e.g. a colour harmony based computational model (Bodrogi et al., 2004; Szabó et al., 2006)

3. APPLICABILITY OF THE CIE COLOUR RENDERING INDEX

3.1 Correlation of the CIE CRI with visual results

It can be concluded from the visual colour rendering results described in Section 2 that the CIE CRI method (CIE, 1995) does not describe well those situations where white LED light sources are involved; i.e. if white LED light sources are visually ranked together with other light sources. Low correlation was found between the visual colour differences and the computed colour differences if the CIE CRI method (CIE, 1995) was applied to calculate those colour differences. One possible reason for these experimental findings is that the CIE R_a number (CIE, 1995) is *one single average number* (calculated from samples of medium saturation) and therefore it is difficult to account for the colour differences related to many different test-colour samples (including saturated colours) (Bodrogi et al., 2004). Another reason was assumed to be the different order of magnitude of the colour differences occurring if the reflecting samples are illuminated by a white LED light source and by other light sources, due to the peculiar spectral power distributions of the white LED light sources "interacting" with the spectral reflectance of the test-colour samples (Bodrogi et al., 2004). This is especially noticeable for the case of test-colour sample No. 9 of the CIE method (CIE, 1995) which is a strong red test-colour sample.

3.2 Applicability of the CIE CRI to white LED light sources

The conclusion of the Technical Committee is that the CIE CRI is generally not applicable to predict the colour rendering rank order of a set of light sources when white LED light sources are involved in this set.

4. RECOMMENDATIONS OF THE TECHNICAL COMMITTEE

4.1 An additional index to supplement the current CIE CRI

The Committee recommends the development of a new colour rendering index (or a *set* of new colour rendering indices), by a Division 1 Technical Committee. This index (or these indices) shall *not replace* the current CIE colour rendering index immediately. The usage of the new index or indices should provide information supplementary to the current CIE CRI, and replacement of CRI will be considered after successful integration of the new index.

4.2 Applicability to all types of light sources

The new supplementary colour rendering index (or set of supplementary colour rendering indices) should be applicable to *all types* of light sources and not only to white LED light sources.

APPENDIX. POSSIBILITIES FOR AN IMPROVED DESCRIPTION OF COLOUR RENDERING

There are many ways to describe the phenomenon of colour rendering mathematically but in order to decide whether a specific description is better than another description, the evaluation of the results of visual colour rendering experiments will always be necessary. And, in any new description, special care must be taken of the most problematic white LED light sources for which the malfunction of the CIE CRI (CIE, 1995) is today anecdotal (van Trigt, 1999; Worthey, 2003), as described in Sections 2 and 3 of this Report.

Possibilities for the description of colour rendering were first re-considered by the CIE in the 1991 Quadrennial Meeting when CIE TC 1-33 on Colour Rendering was formed and a new CRI calculation method ($R96_a$) was developed. This new description was summarized in the chairman's report (CIE, 1999). This $R96_a$ method contained the following new features compared to the standard method (CIE, 1995):

1. test samples were taken from the Macbeth ColorChecker chart instead of the Munsell atlas;
2. six reference illuminants - D65, D50, 4200K black body radiator (P4200), P3450, P2950, and P2700 were used instead of the continuous Planckian/daylight illuminant set (see also Borbély et al., 2001);
3. the CIE chromatic adaptation formula (CIE, 1994) instead of the von Kries transform was used;

4. both the test lamp and the reference lamp were transformed into D65 chromaticity (as the CIELAB space was tested most thoroughly using daylight illumination);
5. colour differences were quantified in CIELAB.

Today, colour experts agree that the CMCCAT2000, CIECAT94, CMCCAT97, and CAT02 chromatic adaptation formulae perform better than the previous chromatic adaptation formulae (Schanda, 2002; CIE, 2004b). It was also realized that CIECAM02 based colour-difference formulae and uniform colour spaces are also capable of predicting both small and large colour differences (Bodrogi et al., 2004; Li et al., 2003). Therefore, the use of a colour appearance model or CIECAM based colour-difference formulae to quantify colour rendering (different formulae can be used for large and small colour differences) looks a straightforward idea. Colour appearance rendering indices have already been proposed (Pointer, 2004). Let us note that today computing time is not a limiting factor. Even a complex chromatic adaptation formula can be computed in fractions of a second.

Another issue is the number of reference sources. Correlated colour temperature turned out to be difficult to define using a visual experiment and a seven-value rank order scale seemed more appropriate (Borbély et al., 2001). In colour rendering computations, it is likely that more than one reference source should be used since the "ideal" colour appearance depends on the user's intent of producing "intimate", "office", or "harsh" environment (Schanda, 2002; Borbély et al., 2001). This points toward the direction of recognizing different intents of light source users in describing the colour rendering phenomenon.

One of the problems is the way of representing the calculated colour differences. Averaging of colour differences calculated from a limited number of test-colour samples may be subject to large error for certain light sources. Spectral power distributions of white LEDs of the RGB cluster type tend to "interfere" with the spectral reflectance curves of modern narrow band colorants (Bodrogi et al., 2004). These surface colours produce large colour differences that are not predictable by one single average number.

It was generally claimed that one single index did not provide enough information for the lighting designer (van Kemenade and van der Burgt, 1995). By taking *many* (e.g. more than a hundred) test-colour samples and dividing all colour-difference values by the value of chroma, a smooth function of hue angle was obtained (van Kemenade and van der Burgt, 1995). (Hue, chroma and lightness shifts may not be visually equally relevant from the point of view of CR, (see also Pointer, 2004). It was claimed (van Kemenade and van der Burgt, 1995) that this function would characterize colour rendering properties better than the CIE CRI. Colour rendering vector fields were also defined in uniform colour spaces or NCS colour diagrams (van Kemenade and van der Burgt, 1995; Sivik, 1980). Vector differences of many test-colour samples between the test and the reference illuminants represent a vector field (van Kemenade and van der Burgt, 1995; Sivik, 1980) and this characterizes colour rendering much more in detail than a single average number (R_a) or a restricted set of numbers (R_i) (CIE, 1995). To show the pivotal colour rendering effects hidden in such a vector field, the so-called colour rendering matrix was introduced (Worthey, 2004). By extending this idea, colour-difference vector fields may also be represented in CIECAM02 J, a_C, b_C (lightness, redness-greenness, blueness-yellowness) colour appearance space. The usage of the J, a_C, b_C space is advantageous because it includes chromatic adaptation.

The rankings of 34 illuminants (including 21 fluorescent lamps, 4 incandescent lamps, 4 HID lamps, CIE illuminants D65 and A, the equi-energy illuminant, and 2 Gaussian illuminants) were compared in a computational study (Guo and Houser, 2004) for nine different indices of light source "colour quality" (CQ, in the sense as described in Section 1), including the CIE CRI R_a, as well as preference and discrimination indices, and the colour appearance rendering index (Pointer, 2004). The rank ordering of the light sources was found to be different on the various CQ scales, and it was concluded again that a single number was not able to account fully for the multi-dimensionality of colour rendering and its related phenomena.

To represent the various CQ scales in a usable way, one author recommended a new communication tool for the end user, the so-called "CQ icon" with 4 "semi-quantitative" ratings for colour rendering (CRI), the user’s ability to make colour-difference judgements (CDI), colour preference (CPI), and the CCT (Radkov, 2006). This concept would yield a 5-rating acronym scale for the first three items, from very low (VL) to very high (VH), and for the fourth item i.e. for CCT, WW for warm white, CW for cool white and DL for daylight. Such a combined index shows the way toward recognizing the different intents of the light source users according to the different primary tasks that the light sources are used for.

The underlying concept of "Color Quality Scale" (Davis and Ohno, 2005), preceded by a similar idea (Schanda, 1985), is that the different dimensions of colour quality – fidelity, preference, and discrimination – are actually highly correlated under many conditions and can be represented by one number, which is requested by the industry in spite of other scientific arguments. The discrepancies occur when object chroma deviates in the direction to increase chroma (possible with certain RGB LEDs) and the CQS attempts to address this by "saturation factor".

Concerning the user’s ability to make colour-difference judgements, a visual experiment on colour discrimination under RGB LED cluster light sources (Viénot et al., 2005) showed that this ability was poor for RGB LED clusters. The impairment of the visual result under RGB LED clusters was due to the absence of power in certain important parts of the spectral power distribution of the RGB LED clusters. This study shows the importance of considering a complex CQ metric as the new supplementary index recommended in Section 4 of this Technical Report.

Quantifying the overlap of colour categories between the test source and the reference source may also improve the description of colour rendering (Boynton et al., 1990; Yaguchi et al., 2001).

The "test sample colour shift" method (CIE, 1995) is based on the original definition of colour rendering. This definition claims that the observer has the ability to "*imagine*" the colour appearance of the surface colours under a reference illuminant and to compare this "expected appearance" with their actual appearance. This implies that there are well-known objects (e.g. skin, leaves, sand, etc.) in the field of view from which the observer knows their "reference appearance". But observers are usually also able to assess the colour rendering of the light source in a scene with only *partial* knowledge of the reflecting samples (e.g. textile samples in a theatre room). It is possible that it is not the colour differences of the samples under the test source and the reference source which is visually relevant but the general appearance of *all* the colours in the field of view under *one* given light source, especially the *relation* between pairs or among triads of colour samples. This may be related to the "internal colour harmony" among the surface colours or the deterioration of this harmony under the test source (Sándor et al., 2003). This may be quantified by a kind of "colour harmony rendering index" (HRI) calculated from the change of the distances between all possible pairs of a set of test colour samples or in a similar way (Bodrogi et al., 2004). This approach may be similar to quantifying the extent of "relational colour constancy" described by the invariance of cone excitation ratios (Foster and Nascimento, 1994).

In a real environment, observers see a "photo-realistic" colour scene and from the impression of this colour scene they conclude whether the test light source is an *acceptable* replacement of the reference source or not. In a recent study (Madár and Schanda, 2006), *visual colour acceptability* and preference judgements tend to yield significantly different results, especially for white RGB LED cluster light sources.

Differences between the concepts of chromatic adaptation and colour constancy have been used to question the common view that chromatic adaptation is the basic mechanism of colour constancy (Brill and West, 1986). Adaptation has a long time course whereas the constancy phenomenon is immediate and similar to the quick visual assessment of colour rendering in a previously unknown scene. To predict colour rendering, it may be possible to consider theories of *colour constancy* e.g. bilinear models (D'Zmura, 1992). During the visual assessment of the colour rendering of a scene, the visual system tries to eliminate the effect of the illuminant and to extract information about surface reflectances in the scene, to ensure colour constancy, in both the chromatically adapted and in the chromatically unadapted eye (Foster, 2004). For illuminants of poor colour rendering properties, this is not possible and colour constancy cannot be established. Therefore, the colours in the visual scene tend to look "strange", even *before* complete chromatic adaptation to the scene.

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