Colour-rendition properties of solid-state lamps

A Žukauskas, R Vaicekauskas, M S Shur

Colour rendition properties of solid-state lamps

A Žukauskas[1*], R Vaicekauskas[2] and M S Shur[3]

[1] Institute of Applied Research, Vilnius University,

Saulėtekio al. 9, bldg. III, Vilnius, LT-10222 Lithuania

[2] Department of Computer Science, Vilnius University,

Naugarduko g. 24, Vilnius, LT-03225 Lithuania

[3] Department of Electrical, Computer, and System Engineering, Rensselaer Polytechnic Institute,

110 8th Street, Troy, NY 12180 USA

[*] E-mail address: arturas.zukauskas@ff.vu.lt

Short title: Colour rendition properties of solid-state lamps

PACS Numbers: 42.66.Qg, 85.60.Jb

Abstract

The applicability of colour quality metrics to solid-state light sources is validated and the results of the assessment of colour rendition characteristics of various lamps are presented. The standard colour rendering index metric (CRI) or a refined colour quality scale metric (CQS) fail to distinguish between two principle colour rendition properties of illumination: the ability to render object colours with high fidelity and the ability to increase chromatic contrast, especially when the spectra of light sources contain a few narrow-band electroluminescence components. Supplementing these metrics by the known figures of merit that measure the gamut area of a small number of test colour samples does not completely resolve this issue. In contrast, the statistical approach, which is based on sorting a very large number of test colour samples with respect of just perceivable colour distortions of several kinds, offers a comprehensive assessment of colour rendition properties of solid-state light sources. In particular, two statistical indices, colour fidelity index (CFI) and colour saturation index (CSI), which are the relative numbers of object colours rendered with high fidelity and increased saturation, respectively, are sufficient to reveal and assess three distinct types of solid state light sources. These are (i) high-fidelity lamps, which cover the entire spectrum with the spectral components present in the wavelength ranges of both 530-610 nm and beyond 610 nm (e.g. trichromatic warm white phosphor converted LEDs, red-amber-green-blue LED clusters, complementary clusters of white and coloured LEDs); (ii) colour-saturating lamps, which lack power in the 530-610 nm wavelength range (e.g. red-green-blue or red-cyan-blue LED clusters); and (iii) colour dulling lamps, which lack power for wavelengths longer than 610 nm (dichromatic daylight phosphor converted LEDs and amber-green-blue LED clusters). Owing to a single statistical format, CSI and CFI can be used for design and optimization of multiwavelength LED clusters providing "smart" illumination with a trade-off between different colour rendition characteristics.

1. Introduction

Solid-state lighting technology, which emerged with the appearance of blue and white light-emitting diodes (LEDs) [1], has a potential to replace inefficient incandescent and discharge-based sources of light [2]. Recent technological advances [3,4] resulted in that LEDs are outperforming conventional lamps in efficiency. Although numerous performance challenges in solid-state lighting still exist [5], the 200-lm/W efficiency barrier that was anticipated for 2020 [6] has been already broken [7].

Despite a rapid progress in efficiency, the potential of solid-state lighting technology in delivering illumination with improved control of colour quality is still almost untapped. Solid-state lighting technology employs the principle of injection electroluminescence in semiconductor junctions used directly or in conjunction with either partial or complete conversion in phosphors [2,8,9]. Such an approach suggests high versatility in composing the spectral power distribution (SPD) of a light source and thus in controlling colour quality of illumination [10]. In particular, light sources with SPDs that contain a few narrow-band electroluminescence components became feasible. Such sources may have colour rendition properties that differ from those of common fluorescent lamps, which emit due only to phosphors.

New possibilities in engineering the spectrum of light sources offered by solid-state technology highlight the fact that colour quality of illumination comprises at least two colour rendition properties: the ability to make colours appear “natural” (colour fidelity) and the ability to make colours appear “vivid” and easily distinguishable (colour saturation) [11]. In the previous-generation lighting technology, the latter property was considered as supplementary, since no common lamps with a pronounced colour-saturating ability were available. Consequentially, the only one widely accepted method of rating lamps in colour quality was the colour rendering index (CRI) [12], which ranks them in how “natural” object colours appear when compared to those under reference broad-band illuminants. However when applications of solid-state sources in lighting emerged, subjective rating of illumination provided by clusters composed of direct-emission LEDs was found to be in an obvious conflict with the standard CRI metric [13–16]. Moreover, the red-green-blue LED clusters have been recently shown to render more object colours with increased saturation rather than with high fidelity [17]. This stimulates a search for new colour quality metrics, which could better comply with the visual ranking and be able to resolve the problem of assessing colour rendition properties of light sources, including those containing narrow-band electroluminescence emissions.

In this paper, we address the problem of colour quality of solid-state light sources in order to validate different metrics and provide guidelines for composing SPDs of single-chip LEDs and LED clusters with different and controllable colour rendition characteristics.

The paper is organized as follows. In section 2, approaches to assessing colour quality of illumination are considered. In section 3, various solid-state lamps, as well as fluorescent lamps, are rated with respect to different colour rendition properties and suggested to categorize into several distinct colour-quality groups. In section 4, a summary of the survey is presented.

2. Colour quality metrics

In this section, several metrics for assessing colour-rendition quality of light sources are considered and compared. We start with CRI, which has been introduced for ranking fluorescent lamps and persists as a standard metric for years, in spite of numerous proposed improvements and alternatives (see, e.g. Ref. 18 for a review). Other metrics considered here are the two recent approaches that were developed in order to meet an increasing demand for the improved assessment of LED-based light sources. These two metrics are the colour quality scale (CQS), which is an attempt to develop a more general approach to colour quality basing on the method of colour differences used in CRI, and the statistical approach to colour quality, which is a method radically different from CRI. Since

CRI and CQS lack means for ranking colour-saturating sources, these metrics are considered in combination with appropriate gamut-area approaches that mitigate this drawback.

*2.1. Colour rendering index and gamut area (U*V*W* colour space)*

CRI is the most widely used metric for rating light sources in colour rendition. Introduced by the International Commission of Illumination (Commission Internationale de l'Éclairage, CIE) in 1965 (see Ref. 12 for the latest edition), CRI relies on numerically estimating colour differences for particular test colour samples when a reference source is replaced by that under assessment. The colour differences are estimated within the $U^*V^*W^*$ colour space (1964 CIE), which is a nonlinear extension of the $u-v$ "uniform chromaticity scale" colour space (1960 CIE) to three dimensions. The lightness index W^* is related to the luminous tristimulus value and the chromaticness indices U^* and V^* are derived from the uv chromaticity coordinates and lightness index. The test colour samples are fourteen samples from the Munsell system, which specify colours in hue, chroma and value (lightness). The reference source, which must have the same correlated colour temperature (CCT) as the source under assessment, is either a blackbody illuminant (for CCT below 5000 K) or daylight phase illuminant (for CCT above 5000 K). A small mismatch between the chromaticity of the reference and tested source is allowed and treated using the von Kries chromatic adaptation method. The special colour-rendering indices are derived from the colour shifts ΔE_i for each test colour sample,

$$R_i = 100 - 4.6\Delta E_i \equiv 100 - 4.6\left[(\Delta U^*)^2 + (\Delta V^*)^2 + (\Delta W^*)^2\right]^{1/2}. \quad (1)$$

The general CRI is the arithmetic mean of eight special CRIs that have moderate chroma (about /6 in average):

$$R_{\mathrm{a}} = \frac{1}{8}\sum_{i=1}^{8} R_i \ . \qquad (2)$$

The general CRI has a maximal value of 100 when the eight colour shifts are almost zero and the scaling parameter 4.6 in equation (1) is selected in such a way that $R_{\mathrm{a}} = 51$ for a warm white halophosphate fluorescent lamp.

Figure 1 illustrates the use of the CRI metric. The circles in the U^*V^* plane of the 1964 CIE colour space stand for the colour points of the eight test colour samples under a light source under assessment, daylight phosphor-converted (pc) LED (CCT = 6042 K), and the squares show the colour points of the same samples under 6042 K daylight illuminant. The bold lines depict the chromaticity shifts that are used in the calculation of the indices.

Despite of widely using CRI for ranking light sources and for optimization of SPDs for both conventional [19] and solid-state [20–24] lamps, this metric has numerous drawbacks [18, 25–27]. The key feature of CRI is treating colour shifts irrespectively of their direction, i.e. the metric exclusively estimates the ability of a light source to render object colours with high fidelity. However, subjective perception of various colour distortions is unequal and depends on the direction of the colour shift. For instance, hue distortions are less tolerated than lightness distortions; and distortions that increase saturation are even preferred [28]. Therefore, a unified approach to different directions of the colour shifts is considered as a serious drawback of CRI. In particular, CRI conflicts with subjective visual preferences when a set of sources under ranking includes sources with SPDs containing few narrow-band components [13–16] (as discussed in section 3, such sources can increase or decrease saturation of a considerable number of object colours).

Another CRI drawback is in that the “uniform chromaticity scale” colour space in fact is far from being uniform in respect of perceptually resolved colour differences. In particular, the MacAdam ellipses [29], which are the regions that comprise chromaticities almost undistinguishable to human vision, have very different dimensions in different parts of the $u-v$ chromaticity diagram. Hence, CRI unequally treats distortions of different object colours.

One more drawback of CRI is using a small number of test colour samples. For instance, using 40 test colour samples closely spaced within a "circle" of equal chroma (/6) revealed that CRI misses distortions in many hue directions [30]. Moreover since vectorial representation of the colour shifts (colour rendition vectors, CRVs) of an enhanced number of test colour samples (~1000) tend to form "clouds" with azimuth (hue) periodicity of colour distortions [31], the eight samples of the general CRI can fall into extremes of such periodic distribution yielding large errors in the assessment. A small number of test colour samples used in CRI might be partially related to modest computational resources at the time when the metric was introduced. However, even a more important reason of avoiding a larger number of test colour samples is the arithmetic averaging of special CRIs in the general CRI; such averaging is not suitable for shifts that are very different in magnitude.

The above drawbacks of CRI, as well as some other shortcomings (e.g. limitations of von Kries chromatic adaptation, equal rating of reference sources, and inconvenient scaling that can yield confusing negative values of the indices) poses a problem of the applicability of this metric for the next-generation lighting technology, solid-state lighting, which offers more versatility in the control of colour quality. To that end, CIE conceded that "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" and recommended the development of a new colour rendering index [27].

Despite some pessimism in using CRI, the main drawback of this metric, the disregard of the colour shift directions, can be considerably mitigated by supplementing R_a by a figure of merit, which quantifies the ability of light sources to make colours appear "vivid" and easy to distinguish. Basically, this ability manifests itself by increasing saturation of object colours. Examples of such colour-saturating-related figures of merit are the flattery index [32] and the colour-discrimination index [33]. A similar figure of merit, which pertains to the CRI metric, is the gamut area index (GAI) [11]. GAI is the relative change in the area of the polygon defined by the coordinates of the eight CRI test colour samples in the 1964 CIE U^*-V^* plane when a reference source is replaced by that under test (see figure 1). GAI employs a single flat-spectrum reference illuminant (CIE illuminant E), which allows comparing sources with various CCT on the absolute scale (sources with lower CCT inherently have lower values of GAI).

Although GAI suffers from many drawbacks peculiar to the general CRI (small number of test colour samples, lack of uniformity of the colour space, etc.), it might be useful for comparing colour rendition characteristics of different sources [11]. However, GAI should be applied with care, since it integrates both positive and negative contributions to gamut variation, i.e. increased saturation of some test colour samples can be compensated by decreased saturation of other samples with a reduced effect on the net gamut area. Figure 1 demonstrates this effect for a daylight pc LED. Here the gamut area under the LED amounts only 85% of that under the reference illuminant, whereas two of the eight test colour samples (3 and 7) gain in saturation.

2.2. Colour quality scale and gamut area scale (CIELAB colour space)

CQS is a metric developed at the National Institute of Standards and Technology (NIST) for mitigating the main drawbacks of CRI [34], especially the absolute focus on colour fidelity. The metric employs a set of 15 test colour samples that have somewhat larger chroma (about /11 in average) than those used in CRI and an improved colour space (CIELAB) that is much more equidistant in respect of perceivable colour differences than the $U^*V^*W^*$ colour space (figure 2). One of the main ideas of CQS is to take into account subjective colour saturation preferences by quantifying the ability of a light source to render object colours with high fidelity and the ability to render colours with increased saturation within an integral figure of merit. This is achieved through the introduction of a reduced colour difference, which excludes the increase of saturation. For an *i*th test colour sample, the reduced colour difference can be presented as

$$\Delta E_i^* = \left[(\Delta H)^2 + \left(\mathrm{Re}\sqrt{-\Delta C} \right)^4 + (\Delta L)^2 \right]^{1/2}, \tag{3}$$

where ΔH, ΔC, and ΔL are the shifts in hue, chroma, and lightness, respectively, when a reference source is replaced by that under assessment. Bold lines in figure 2 depict the reduced colour shifts with only negative chromatic shifts taken into account (samples 1, 2, 3, 8, 9, 10, 11, and 15) and with positive chromatic shifts excluded (samples 4, 5, 6, 7, 12, 13, and 14).

Another improvement of the CQS metric is using the root-mean-square (RMS) of the reduced colour differences in order to ensure that a large colour difference for any sample has a higher influence on the overall rating:

$$\Delta E_{\mathrm{RMS}}^* = \sqrt{\frac{1}{15}\sum_{i=1}^{15} (\Delta E_i^*)^2} \; . \tag{4}$$

In order to avoid negative values of the score, a nonlinear conversion to a 0–100 rating scale is used in the CQS metric:

$$\mathrm{CQS} = 10 \ln\{\exp[10 - 0.301\, \Delta E_{\mathrm{RMS}}^*] + 1\}, \tag{5}$$

where 0.301 is the scaling factor selected such that that the average CQS score for a standard set of fluorescent lamp spectra is equal to the average general CRI for the same set of lamps.

One more improvement of the CQS metric in respect of CRI is the derating of light sources with very low and very high CCTs (below 3500 K and above 6500 K, respectively) in order to take into account the reduced gamut area of the set of the test colour samples. (However, such a derating is ambiguous, since some individuals exhibit the effect of colour constancy that compensates the reduction of the gamut area [35].)

Despite the regard to colour saturation preferences, the CQS metric is unable to completely distinguish between light sources that have different ability in saturating object colours. For instance, a source that renders the colour of a *j*th sample with increased chroma ($\Delta C_j > 0$) can have the same CQS score as another source that renders the colour of the same sample without increased ($\Delta C_j = 0$). Another drawback of CQS is still a relatively low number of test colour samples comparing to the actual number of object colours distinguished by human vision.

The former drawback of the CQS metric can be mitigated in the same way as in the case of CRI, i.e. by the supplementing the CQS score by an appropriate gamut-area-based figure of merit. By analogy with GAI, which is the supplement to CRI, a relative change in the area of the polygon defined by the coordinates of the 15 CQS test colour samples in the a^*–b^* plane of the CIELAB colour space can be employed. Such a relative change (designated here as the gamut area scale, GAS) has been already used for the optimization of SPDs of tetrachromatic LED-based light sources [23]. In order to completely match GAS with CQS, derating of the sources with extreme values of CCT can be applied [34] instead of using a single reference source as in GAI. It is to be noted that GAS has the same limitations as GAI due to the compensation of positive and negative shifts in chroma of different test colour samples (see figure 2).

2.3. Statistical approach to colour rendition

One of the main shortcomings of the CRI metric, a small number of test colour samples, is still present in CQS and is difficult to avoid when an averaging of the colour shifts is used. For a large number of test samples, several alternative approaches can be applied. For instance, a large number of test colour samples can be subjectively sorted into several categories basing on colour names.

The results of sorting for a tested lamp can be compared in respect of a reference illuminant and quantified by appropriate indices corresponding to various colour rendition characteristics. Several metrics of such categorical colour rendering have been proposed [36,37]. Another example of a large-sample-number approach is graphical analysis of a set of CRVs [26,31]. An advanced approach is the computational sorting of the CRVs to several groups depending on the type of colour distortion and statistical analysis of the sorting results [38].

A statistical approach introduced in Ref. 38 relies on several basic principles. First, it avoids using colour spaces, which in fact are non-ideal analytical approximations of perceptually uniform colour space. Instead, the behaviour of the CRVs is analysed in respect of the colour-discrimination shapes, which are built basing on the experimental data on just perceivable colour and luminance differences estimated individually for each colour test sample. Figure 3 shows such a shape, which is an elliptical cylinder with the cross-section identical to a triple-sized region of the just perceivable chromaticity and the half-height equal to three times the just perceivable luminance difference. The regions of the just perceivable chromaticity are the interpolated MacAdam ellipses [29], which can be presented within any colour space; and the just perceivable luminance difference is 0.7% [39]. The second principle of the statistical approach is in that a CRV is not continuously quantified in magnitude and direction, but discretely scored to a particular colour rendition index depending on its behaviour in respect of the colour-discrimination shape. If the CRV for a test colour sample dos not escape from the shape, the colour is considered as rendered with high fidelity (indistinguishably from the reference source) and the sample is scored to colour-fidelity index (CFI). If the CRV escapes from the shape, the sample is scored to at least one of several statistical colour-distortion indices depending on the projections of the vector that exceed the size of the shape. For instance, when a CRV has an excess projection directed toward increased or decreased chroma, the sample can be scored to the colour saturation index (CSI) or colour dulling index (CDI), respectively. Similarly, a CRV with an excess projection directed toward different hue or along the luminance (vertical) axis can be scored to the hue distortion index (HDI) or luminance distortion index (LDI). (CDI and LDI are introduced here in addition to CFI, CSI, and HDI defined in Ref. 38). Each index measured in the percentage of the scored samples quantifies a particular colour rendition characteristic of a light source within the single statistical format. An extended statistical representation of colour rendition characteristics of a light source (e.g. behaviour of the CRVs of particular hues) is a colour quality chart [38], which displays the CRVs scored to different indices within an appropriate colour space (e.g. CIELAB).

Differently from colour-shift-averaging metrics (CRI and CQS), the magnitudes of the CRVs are not decisive in the statistical approach, once a very large number of test colour samples is employed (a larger value of a colour-distortion index implies a higher possibility of the presence of CRVs with larger respective projections). An appropriate set of test colour samples is the spectrophotometrically calibrated palette of 1269 Munsell samples [40].

It should be noted that the statistical metric exploits MacAdam ellipses, which have been originally defined for a constant luminance (~48 cd/m^2) [29]; therefore this luminance value is assigned to all test colour samples irrespectively of their colour lightness. Further development of the method is required in order to extend the assessment of colour distortions for test colour samples having particular lightness under conditions of different luminance. (It is to be noted that CRI and CQS, which use lightness scales, have an opposite drawback in that luminance, which is important in colour discrimination, is not specified and taken into consideration). Also, subjective validation of the statistical method needs developing new approaches because of a very large number of test colour samples used. Finally, the statistical approach requires solving some general problems of colour rendition such as the problems of chromatic adaptation, colour constancy, reference sources, and colour appearance of the samples with different backgrounds taken into account.

3. Solid-state lamps with different colour rendition properties

Different metrics described in the previous section can be used for assessing colour rendition properties of light sources. Irrespectively of a metric used, the two basic colour quality characteristics of lighting, the ability to render surface colours with high fidelity and the ability to saturate (desaturate) colours, are probably the most important ones for giving subjective preferences of illumination and for rating light sources in colour rendition quality.

In this section, various solid-state sources of light, as well as their ancestors, fluorescent lamps, are considered. The sources are rated using the three above approaches, the general CRI in combination with the relative gamut area for eight standard test samples in the *V**U*W** colour space (GAI), CQS in combination with the relative gamut area for 15 test colour samples in the CIELAB colour space (GAS), and the statistical approach, which rely on McAdams ellipses rather than on a colour space and employs 1269 test colour samples.

The lamps under consideration are attributed to three conditional groups of, namely, high-fidelity, colour-saturating, and colour-dulling lamps, respectively. Within each group, we compare lamps in terms of colour-fidelity indices (R_a, CQS, and CFI), colour-saturation indices (GAI, GAS, CSI, and CDI), as well as two additional statistical indices for hue and luminance distortions (HDI and LDI, respectively).

Here, versatility of solid-state lighting technology in the control of colour rendition properties is demonstrated by simulating SPDs of multiwavelength clusters that are composed of standard coloured and white LEDs. As a model set of commercial LEDs, the Philips Lumileds Lighting Luxeon® Rebel LED family of 10 typical LEDs [41] that meet the needs of display, signage, and lighting industry was employed. This family comprise direct-emission royal-blue (452 nm peak wavelength), blue (469 nm), cyan (512 nm), and green (523 nm) InGaN LEDs; direct-emission amber (591 nm), red-orange (625 nm), and red (637 nm) AlGaInP LEDs; and InGaN-based pc amber (589-nm), daylight and warm white LEDs. The SPDs of the LEDs used in the simulation of multiwavelength lamps were measured at a forward current of 350 mA and at a temperature of the metal pad of 25° C.

3.1. *High-fidelity lamps*

We define high-fidelity light sources as those rendering more than half object colours indistinguishably from reference sources (CFI > 50%) and having low values of statistical indices that signify increased of decreased saturation and distortions of hue and luminance (CSI CDI, HDI, and LDI, respectively). Such lamps are able of mimicking sunlight (for high CCTs) or incandescent (halogen) lamps (for low CCTs) and can be used for illuminating scenes that require extreme naturalness of colours. The SPDs of high-fidelity lamps have multiple narrow-band components that tightly cover the visible spectrum. Because of a large number of components needed, selection of the components and finding the partial fluxes of those require solving problems of additive colour mixing through optimization of target functions within multiparametric spaces [20,21,24].

Colour rendition indices of high-fidelity lamps are presented in table 1. Light sources with CFI > 50% are seen to typically have R_a in excess of 90 and CQS scores smaller by several points. The colour-saturating ability of these lamps is low and the gamut-area indices are very similar (GAS is around 100% and GAI is around 60% and 100% for CCT of 3000 K and 6500 K, respectively).

Among conventional light sources, this family is contributed by fluorescent multiband lamps, which convert UV radiation to visible light with a rich spectrum provided by a set of wide-band and narrow-band phosphors [42]. Typically, such lamps have CFI of about 70%, and the statistical colour-distortion indices have low values (mostly below 10%).

Fluorescent triphosphor lamps have SPDs that are composed of narrow-band phosphor emissions due to rare-earths ions [38,43] and therefore are deficient in some spectral components. Such lamps with R_a around 80 and CFI somewhat below 50% can be considered as medium-fidelity light sources, which are suitable for many applications in general lighting. Statistical indices (table 1) show that triphosphor lamps also have low colour saturating ability, but noticeably distort hues (HDI from 20% to 30%). Besides, a considerable number of test colour samples appear dull and have distorted luminance. However, CFI is still high to exceed any of distortion-related statistical indices (CSI, CDI, HDI, and LDI).

Solid-state lighting technology, which employs direct and/or phosphor-converted electroluminescence, offers more versatility in designing high-fidelity lamps. For instance for CCT = 6500 K, 100% CFI can be attained in optimized model multiwavelength sets of coloured emitters (semiconductor junctions and/or phosphors) with almost equidistant peak positions, such as a trichromatic set (456 nm, 550 nm, and 664 nm; 88-nm band width), tetrachromatic set (453 nm, 521 nm, 586 nm, and 652 nm; 51-nm band width), or a pentachromatic set (451 nm, 501 nm, 552 nm, 601 nm, and 653 nm; 30-nm band width) [43,44]. However when the objective function is a figure of merit based on a small number of test colour samples, the model SPDs are subjected to a significant variation of the peak positions. For instance, the pentachromatic set of 30-nm components that is optimized in respect of R_a have noticeably shorter peak wavelengths of 444 nm, 487 nm, 530 nm, 572 nm, and 622 nm, respectively, [43] and CFI reduced to 96%. This demonstrates that maximizing R_a can result in minimizing already undistinguishable chromaticity shifts within the MacAdam ellipses for the eight standard samples and in a loss of fidelity of colour rendition for a larger number of other samples (about 50 in this case). Same applies to CQS, which employs only 15 test colour samples.

Of commercial single-chip LEDs, warm white pc LED, which is an InGaN-based LED with partial conversion of blue electroluminescence in two phosphors (yellow and red), can be attributed to high-fidelity light sources (CFI = 61%). This LED almost does not render object colours with increased saturation and has a modest LDI. The main drawback of this light source is a rather high portion of dulled colours (CDI = 25%). The overall rating of colour quality of the warm white pc LED is in between multiband and triphosphor fluorescent lamps.

Practical solid-state lamps with improved colour fidelity can be realized by assembling commercial direct-emission and phosphor converted LEDs to multiwavelength clusters. Figure 4(a) shows examples of SPDs for tetrachromatic RAGB clusters composed of standard coloured LEDs. The selection of the LEDs and adjusting their relative partial fluxes was carried out through the solution of an optimization problem with CFI used as an objective function. Within the family of commercial LEDs employed, the highest values of CFI were attained for a tetrachromatic set of red 637-nm, pc amber 589-nm, green 523-nm, and blue 452-nm LEDs (RpcAGB cluster). Of 1269 test colour samples, high fidelity of colour rendition was obtained for 88% and 77% samples for CCT of 3000 K and 6500 K, respectively. Meanwhile, all statistical colour-distortion indices (CSI, CDI, HDI, and LDI) dropped to marginal values. It is to be noted that optimization of practical high-fidelity clusters in respect of R_a or CQS usually results in the selection of the same set of LEDs, since the choice of peak wavelengths is small. For instance, the above tetrachromatic set optimized in respect of R_a (CCT = 3000 K) has partial fluxes of the narrow-band components that differ by less than 10% from those for maximized CFI and the value of CFI is reduced by only 1%.

High CFIs are also available for clusters, where coloured LEDs complement white phosphor-converted LEDs thus mitigating deficiency in some spectral components [45]. In order to preserve the chromaticity of the lamp on the daylight or blackbody locus, at least two coloured LEDs are to be employed. Figure 4(b) shows SPDs of complementary light sources composed of a warm white LED and two coloured LEDs. Colour-fidelity characteristics of such sources (table 1) are considerably higher than those of the solitary warm white LED and are similar to those of tetrachromatic clusters that comprise a pc amber LED. Typically, values of CFI in excess of 80% can be attained.

Even higher colour-fidelity of illumination can be provided by complementary lamps composed of a warm white LED and three coloured LEDs (figure 4(c)). These lamps have CFI well above 90%. Similar extreme colour-fidelity characteristics are obtained for a pentachromatic cluster composed of coloured LEDs (figure 4(d)). The latter cluster differs from the above tetrachromatic one in that the second blue LED (469-nm) is added (RpcAGBB cluster).

3.2. Colour-saturating lamps

Colour-saturating lamps can be defined as those rendering colours of the major portion of a high number of test colour samples with increased saturation (CSI > 50%). Such lamps can find applications that require improved colour discrimination and/or increased colourfulness, e.g. in some work environments, as well as in commercial, entertainment, and architectural lighting. Colour-saturating lighting is subjectively preferred in respect of high-fidelity lighting in short-term visual experiments, although it is a question whether colour-saturating preferences persisted in general lighting, which implies long-run visual convenience. The SPDs of colour-saturating lamps basically differ from those of high-fidelity lamps in that the spectrum is void of the component in the 530-610 nm wavelength range.

Colour rendition indices of colour-saturating lamps are presented in table 2. Basically, such lamps have reduced colour-fidelity indices and a very low CDI and noticeably distort hue and luminance of surfaces. This category of lamps is peculiar in that their CQS score is larger than R_a due to the intentional disregard of colour-saturating effect in the CQS metric. Also, one can notice that the colour saturating effect can be higher at lower CCTs.

Conventional colour-saturating light source is a neodymium-glass filtered incandescent lamp, which is known for years [46]. Such lamp renders about 52% of 1269-element Munsell palette with increased saturation, while still a considerable portion of test colour samples (37%) are rendered with high fidelity and HDI and LDI have moderate values. It is to be noted that gamut-area indices

(GAI and GAS) of the lamp do not substantially differ from those of high-fidelity lamps with low CCT. This indicates on the insensitivity of these indices to colour-saturating properties of some light sources.

Another example is a colour-saturating source comprising three narrow-band red, green, and blue emitters [47,48], for instance a lamp known from experiments on visual perception, which contains 10-nm wide components with the spectral peaks at 630, 530, and 450 nm, respectively [48]. This RGB lamp has CSI in the range of 70% to 80% depending on CCT and huge gamut-area indices. However many test colour samples, especially those with increased saturation, experience hue and luminance distortions (typically HDI and LDI are around 70%) and colours of very few samples (< 10%) are rendered with high fidelity. High colour saturating effect can be also attained for a dichromatic blend of narrow-band red and green emitters (not shown in table 2). However, such an RG lamp has even higher HDI (actually, no other hues except red and green are rendered).

Design rules for colour-saturating solid-state lamps were considered in Ref. 17. Such lamps are direct-emission-LED RGB clusters that do not cover the spectral region between 530 nm and 610 nm. Provided that this spectral gap is kept unimpaired, the colour-saturating ability of the clusters is rather insensitive to the peak positions of the LEDs. Several triads of commercial coloured LEDs can be employed, for instance, a 637-512-469-nm RCB cluster or a 637-523-452-nm RGB cluster (see table 2 and figure 5). Such clusters can have CSI around 70% and higher, low CFI and high values of HDI and LDI, similarly to the narrow-band RGB emitter. Because of the absence of the 530–610-nm component, colour-saturating LED clusters have reduced LER in comparison with other lamps. Again, since the choice of the peak wavelengths of commercial LEDs is small, maximization of any of the three colour-saturation indices (CSI, GAI or GAS) can be used for the selection of the RGB components with very similar result.

3.3. Colour-dulling lamps

Some light sources have CDI in excess of 50% and therefore can be designated as colour-dulling lamps. The general CRI of these lamps is below 80 and currently they are only used in general lighting applications where no regard to colour quality is paid. (However, a potential for using them in specific applications, were desaturated colours might be preferred, e.g. for colour vision relaxation or for some medical or cultural environments, still needs unveiling.) The SPDs of such lamps must have a component in the 530-610 nm range, which is absent in colour-saturating lamps. However differently from high- and medium-fidelity lamps, they usually lack the component in the wavelength range beyond 610 nm and in some cases rely only on a dichromatic yellow-blue (YB) system [26].

Colour rendition indices of colour-dulling lamps are presented in table 3. The lamps are seen to render a modest portion of object colours with high fidelity (CFI <30%) and have R_a and CQS score very similar to those of colour-saturating lamps (however, none of these two indices has advantage over another one as in the case of colour-saturating lamps). Almost no object colours gain in chroma (CSI is close to zero) and HDI and LDI of practical colour-dulling lamps are somewhat smaller than those of colour-saturating counterparts. Also, higher values of CDI are attained at lower CCT.

Conventional colour dulling lamps are dichromatic halophosphate fluorescent lamps. They have CDI of 50% to 70%.

Table 3 also displays data for colour-dulling YB lamps composed of 30-nm wide emitters, which have extremely high CDI, as well as HDI and LDI (no hues other than blue and yellow are rendered [26]). With increasing bandwidth, the modelled YB lamps exhibit a decrease in all colour-distorting statistical indices and an increase in fidelity indices. The colour-dulling effect persists (CDI > 50%) for the band widths of the components up to 100 nm.

Of practical solid-state light sources, a typical colour-dulling lamp is the two-component daylight white LED with partial conversion of blue light emitted by the InGaN chip to yellow light emitted by cerium-doped yttrium-aluminium-garnet (YAG) phosphor. This LED has CDI of 53% and also makes many test colour samples appear as having distorted hue and luminance.

Colour-dulling lamps can also be composed of practical coloured LEDs. The highest values of CDI are obtained for trichromatic LED clusters containing direct-emission amber, green, and blue LEDs. Figure 6 shows examples of SPDs for the trichromatic AGB clusters containing standard coloured LEDs (amber 591-nm, green 523-nm, and blue 452-nm). These clusters have CDI of 51% and 67% for CCT of 3000 K and 6500 K, respectively. It should be noted that the AGB clusters have the largest LER of all solid-state lamps due to the absence of the component in the spectral range beyond 610 nm.

4. Discussion and conclusions

In the following we discuss and summarize the above analysis of different colour quality metrics and assessment of colour rendition properties of various solid-state lamps.

High values of R_a and CQS score (≥90) indicate on high colour fidelity of a lamp. However these two figures of merit, which actually measure either only colour fidelity (CRI) or evaluate colour fidelity with regard to colour-saturating preferences (CQS), fail to distinguish between lamps that have different colour-saturating properties (except when used both, the condition CQS > R_a indirectly indicates on the colour-saturating ability). This is the reason for that the CRI and CQS metrics, which average colour rendition data for a relatively small number of test colour samples, have limited applicability in solid-state lighting technology, which exploits narrow-band components not only in high-fidelity lamps, but also in colour-saturating lamps, such as RGB LED clusters. This drawback can be mitigated by supplementing the CRI and CQS metrics by gamut-area indices, such as GAI or GAS, respectively. However because of a poor overlap of the narrow-band components of the solid-state lamps with the reflection spectra of a small number of test colour samples involved and compensation of the positive and negative contributions to saturation within the gamut area, in some cases these gamut-area indices are rather insensitive and even miss the colour-saturating effect. Also GAI, which is based on a single reference illuminant, is somewhat inconvenient in that it always has values below 100 for low-CCT lamps, even for those exhibiting a high colour-saturating effect in respect of a blackbody radiator.

To that end, statistical approach, which is based on sorting a large number of test colour samples, offers a radically improved assessment of colour quality of lighting. Although our analysis of various light sources involved a rather large number of statistical indices (five), the statistical metric can identify the principle colour rendition properties of lamps basing on only two of them, CFI and CSI. High fidelity lamps have high CFI and low CSI; colour-saturating lamps have low CFI and high CSI; and colour-dulling lamps have both CFI and CSI low. It also important that differently from the supplementary CRI/GAI and CQS/GAS metrics, the statistical approach measures different colour rendition characteristics within a single format, the percentage of test colour samples rendered in different way. This makes the statistical metric convenient not only in communication to the end user, but also in trading off different colour rendition characteristics within a single solid-state lamp, such a “smart” LED cluster with the individual control of the coloured fluxes.

Colour rendition characteristics of conventional white pc LEDs depend on the number of phosphors used. Dichromatic InGaN:YAG:Ce^{3+} daylight LED actually is a colour-dulling lamp, which can find only limited applications in general lighting. Warm white trichromatic LED with partial conversion already renders the major portion (~60%) of object colours with high fidelity. Meanwhile, one can anticipate that pc LEDs with complete conversion within a triphosphor blend can compete in extreme colour fidelity with multiband fluorescent lamps.

LED clusters offer more versatility in colour rendition engineering. RGB and AGB clusters composed of narrow-band direct-emission LEDs are the lamps with high colour-saturating and colour-dulling ability, respectively. Since the narrow-band RAGB LED cluster has rather high colour-fidelity indices [30,38], colour quality of such a cluster can be traded off between all three colour-rendition properties (fidelity, saturating, and dulling) by the variation of the partial fluxes of the coloured LEDs.

LED clusters with extreme colour-fidelity indices require covering the entire spectrum. In particular, a broad-band 530–610-nm component that prevents from colour saturating and a component in the wavelength range beyond 610 nm that that prevents from colour dulling are required. Such clusters can be implemented in several ways by ether complementing white pc LEDs by two or three direct-emission coloured LEDs or by using a multichip approach based on at least four coloured LEDs. In the latter case, broad-band pc coloured LEDs, such as pc amber LED, are preferred in order to reduce the number of components. An example of such a lamp is the RpcAGB cluster. Provided that the driving circuitry of this cluster allows extinguishing the amber LED and adjusting the partial fluxes of the rest (RGB) LEDs, illumination with dynamically traded off colour fidelity and colour saturating can be realized. The development and subjective assessment of such clusters with a dynamical trade-off between different colour rendition characteristics is a subject of our future work.

Acknowledgments

The work at RPI was partially supported by the National Science Foundation (NSF) Smart Lighting Engineering Research Center (# EEC-0812056).

References

[1] Nakamura S and Fasol G 1997 *The Blue Laser Diode: GaN Based Light Emitters and Lasers* (Berlin: Springer)

[2] Žukauskas A, Shur M S and Gaska R 2002 *Introduction to Solid-State Lighting* (New York: Wiley)

[3] Krames M R, Shchekin O B, Mueller-Mach R, Mueller G O, Zhou L, Harbers G and Craford M G 2007 Status and future of high-power light-emitting diodes for solid-state lighting *J. Displ. Technol.* **3** 160–75

[4] Mottier P (ed) 2009 *LEDs for Lighting Applications* (Hoboken, NJ: Wiley)

[5] Crawford M H 2009 LEDs for solid-state lighting: Performance challenges and recent advances *IEEE J. Sel. Top. Quantum Electron*. **15** 1028–40

[6] Tsao J Y 2004 Solid-state lighting: Lamps, chips, and materials for tomorrow *IEEE Circ. Dev. Mag*. **20** 28–37

[7] Cree, Inc. 2010 Cree breaks 200 lumen per watt efficacy barrier, Web address: http://www.cree.com/press/press_detail.asp?i=126523209125

[8] Steigerwald D A, Bhat J C, Collins D, Fletcher R M, Holcomb M O, Ludowise M J, Martin P S and Rudaz S L 2002 Illumination with solid state lighting technology *IEEE J. Sel. Top. Quantum Electron*. **8** 310–20

[9] Schubert E F and Kim J K 2005 Solid state light sources getting smart *Science* **308** 1274–8

[10] Shur M and Žukauskas A 2005 Solid-state lighting: Toward superior illumination *Proc. IEEE* **93** 1691–703

[11] Rea M S and Freyssinier-Nova J P 2008 Color rendering: A tale of two metrics *Color Res. Appl*. **33** 192–202

[12] CIE 1995 Method of measuring and specifying color rendering properties of light sources *Publication* No 13.3

[13] Narendran N and Deng L 2002 Color rendering properties of LED light sources *Proc. SPIE* **4776** 61–7

[14] Shakir I and Narendran N 2002 Evaluating white LEDs for outdoor landscape lighting application *Proc. SPIE* **4776** 162–70

[15] Nakano Y, Tahara H, Suehara H, Kohda J and Yano T 2005 Application of multispectral camera to color rendering simulator *Proc. of the AIC Colour 05 – 10th Congr. Int. Colour Assoc. (Granada, Spain, 8–13 May 2005)* pp 1625–8

[16] Sándor N and Schanda J 2006 Visual color rendering based on color difference evaluations *Lighting Res. Technol.* 38 225–39

[17] Žukauskas A, Vaicekauskas R and Shur M 2010 Solid-state lamps with optimized color saturation ability *Opt. Express* **18** 2287–95

[18] Guo X and Houser K W 2004 A review of colour rendering indices and their application to commercial light sources *Lighting Res. Technol.* **36** 183–99

[19] Thornton W A 1971 Luminosity and color-rendering capability of white light *J. Opt. Soc. Am.* **61** 1155–63

[20] Žukauskas A, Vaicekauskas R, Ivanauskas F, Gaska R and Shur M S 2002 Optimization of white polychromatic semiconductor lamps *Appl. Phys. Lett.* **80** 234–6

[21] Žukauskas A, Vaicekauskas R, Ivanauskas F, Shur M S and Gaska R 2002 Optimization of white all-semiconductor lamp for solid-state lighting applications *Int. J. High Speed Electron. and Systems* **12** 429–37

[22] Ries H, Leike I and Muschaweck J 2004 Optimized additive mixing of colored light-emitting diode sources *Opt. Eng.* **43** 1531–6

[23] Ohno Y 2005 Spectral design considerations for white LED color rendering *Opt. Eng.* **44** 111302

[24] Mirhosseini R, Schubert M F, Chhajed S, Cho J, Kim J K and Schubert E F 2009 Improved color rendering and luminous efficacy in phosphor-converted white light-emitting diodes by use of dual-blue emitting active layers *Opt. Express* **17** 10806

[25] van Trigt C 1999 Color rendering, a re assessment *Color. Res. Appl.* **24** 197–206

[26] Worthey J A 2003 Color rendering: Asking the question *Color Res. Appl.* **28** 403–12

[27] CIE 2007 Colour rendering of white LED sources *Publication* No 177

[28] Hashimoto K and Nayatani Y 1994 Visual clarity and feeling of contrast *Color Res. Appl.* **19** 171–185

[29] MacAdam D L 1942 Visual sensitivities to color differences in daylight *J. Opt. Soc. Am.* **32** 247–74

[30] Stanikūnas R, Vaitkevičius H, Švegžda A, Viliūnas V, Bliznikas Z, Breivė K, Vaicekauskas R, Novičkovas A, Kurilčik G, Žukauskas A, Gaska R and Shur M S 2005 Polychromatic solid-state lamps versus tungsten illuminant: hue changes of Munsell samples *J. Phys. D Appl. Phys.* **38** 3202–7

[31] van der Burgt P and van Kemenade J 2006 The challenge in communicating color rendition of light sources, The balance between simplicity and accuracy *Proc. of the 6th Int. Symp. Light and Color (Orlando, FL, EPRI Lighting Research Office, 5–8 February 2006)* S10

[32] Judd D B 1967 A flattery index for artificial illuminants *Illum. Eng.* **62** 593–8

[33] Thornton W A 1972 Color-discrimination index *J. Opt. Soc. Am.* **62** 191–4

[34] Davis W and Ohno Y 2005 Toward and improved color rendering metric *Proc. SPIE* **5941** 59411G

[35] Zukauskas A, Viliunas V, Stanikunas R, Svegzda A, Vaitkevicius H, Bliznikas Z, Breive K, Vaicekauskas R, Novickovas A, Kurilcik G, Gaska R and Shur M S 2004 Color perception under illumination by quadrichromatic solid-state lamp *Proc. SPIE* **5530** 347–53

[36] Boynton R M, Fargo L and Collins B L 19909 Categorical color rendering of four common light sources *Color Res. Appl.* 15 222–30

[37] Yaguchi H, Takahashi Y and Shioiri S 2001 A proposal of color rendering index based on categorical color names *Proc. of the Int. Lighting Congr.(*Istanbul, 12–14 September 2001*)* vol. II, pp. 421–6

[38] Žukauskas A, Vaicekauskas R, Ivanauskas F, Vaitkevičius H, Vitta P and Shur M S 2009 Statistical approach to color quality of solid-state lamps *IEEE J. Sel. Top. Quantum Electron.* **15** 1753–62

[39] Wyszecki G and Stiles W S 2000 *Color Science: Concepts and Methods, Quantitative Data and Formulae* (New York: Wiley) Chapter 7

[40] Spectral Database, University of Joensuu Color Group, Web address: http://spectral.joensuu.fi/

[41] LUXEON Rebel, Web address: http://www.philipslumileds.com/products/luxeonrebel

[42] Coaton J R and Marsden A M (eds) 1997 *Lamps and Lighting* (Butterworth-Heinemann: Oxford) Chapter 10

[43] Žukauskas A, Vaicekauskas R, Ivanauskas F, Vaitkevičius H and Shur M S 2008 Rendering a color palette by light-emitting diodes *Appl. Phys. Lett.* **93** 021109

[44] Žukauskas A, Vaicekauskas R, Ivanauskas F, Vaitkevičius H and Shur M S 2008 Spectral optimization of phosphor-conversion light-emitting diodes for ultimate color rendering *Appl. Phys. Lett.* **93** 051115

[45] Vitta P, Zukauskas A, Gaska R and Shur M S 2004 White complementary solid-state lamp *Leukos* **1** 59–66

[46] Bouma P J 1938 The colour reproduction of incandescent lamps and ‘Philiphan’ glass *Philips’ Technical Review* **3** 47–9

[47] Thornton W A 1973 Fluorescent lamps with high color-discrimination capability *J. Illum. Eng. Soc.* **3** 61

[48] McCann J J, McKee S P and Taylor T H 1976 Quantitative studies in retinex theory: A comparison between theoretical predictions and observer responses to the ‘Color Mondrian’ experiments *Vision Res.* **16** 445–58

Figure captions

Figure 1. Colour coordinates of the eight colour test samples used in the CRI metric in the U^*-V^* plane of the 1964 CIE colour space. The circles and squares show the coordinates under daylight pc LED and the reference source (6042 K daylight phase illuminant), respectively. The thin lines delineate the gamut areas of the two sets of coordinates and the bold lines are the colour shifts used in the calculation of the colour rendering indices.

Figure 2. Colour coordinates of the 15 colour test samples used in the CQS metric in the a^*-b^* plane of the CIELAB colour space. The circles and squares show the coordinates under daylight pc LED and the reference source (6042 K daylight illuminant), respectively. The thin lines delineate the gamut areas of the two sets of coordinates and the bold lines are the reduced colour shifts (with positive increase in chromatic shifts excluded) used in the scoring.

Figure 3. Colour discrimination shape (elliptical cylinder) used in the statistical approach to the assessment of colour quality of lighting. The cross-section of the cylinder is the three-step MacAdam ellipse and the half-height is 2% of luminance.

Figure 4. Spectral power distributions of high-fidelity multiwavelength solid-state lamps for correlated colour temperature of 3000 K (−−−−−) and 6500 K (- - - - -). (*a*) Red-pc_amber-green-blue LED clusters, (*b*) warm white-green-red and warm white-cyan-blue complementary LED clusters, (*c*) warm white-red-amber-cyan and warm white-amber-cyan-blue complementary LED clusters, (*d*) red-pc_amber-green-blue-blue LED clusters.

Figure 5. Spectral power distributions of colour-saturating multiwavelength solid-state lamps for correlated colour temperature of 3000 K (−−−−−) and 6500 K (- - - - -). (*a*) Red-cyan-blue LED clusters, (*b*) red-green-blue LED clusters.

Figure 6. Spectral power distributions of colour-dulling amber-green-blue LED clusters for correlated colour temperature of 3000 K (−−−−−) and 6500 K (- - - - -)..

Table 1. Colour rendition indices of high-fidelity lamps.

Lamp type	CCT (K)	R_a	CQS	**CFI**	GAI	GAS	CSI	CDI	HDI	LDI	LER (lm/W)
Fluorescent multiband	3023	92	89	**74**	66	98	7	9	8	15	(266)
	7078	96	94	**90**	104	100	2	0	2	3	(229)
Fluorescent triphosphor	2770	82	75	**46**	60	98	13	20	23	31	(307)
	6088	80	77	**40**	94	94	2	30	29	34	(254)
Warm white pc LED	3360	90	88	**61**	65	96	0	25	9	12	294
RpcAGB LED cluster	3000	95	90	**88**	63	101	1	3	5	3	344
(637 nm/589 nm/523 nm/452 nm)	6500	93	90	**77**	102	103	1	4	12	6	313
WWGR LED cluster (WW/523 nm/625 nm)	3000	94	93	**83**	63	101	9	1	1	2	302
WWCB LED cluster (WW/512 nm/452 nm)	6500	95	94	**84**	102	103	9	0	4	2	270

WWRAC LED cluster (WW/637 nm/591 nm/512 nm)	3000	98	95	**98**	60	98	0	1	1	1	297
WWACB LED cluster (WW/591 nm/512 nm/452 nm)	6500	97	95	**95**	99	101	0	1	1	0	275
RpcAGBB LED cluster	3000	97	93	**95**	61	99	1	2	2	1	340
(637 nm/589 nm/523 nm/469 nm/452 nm)	6500	96	93	**94**	99	100	0	2	4	0	306

Table 2. Colour rendition indices of colour-saturating lamps.

Lamp type	CCT (K)	R_a	CQS	CFI	GAI	GAS	**CSI**	CDI	HDI	LDI	LER (lm/W)
Neodymium glass filtered incandescent lamp	2757	77	83	37	68	107	**52**	0	15	28	–
Narrow-band RGB emitter (630 nm/530 nm/450 nm)	3000	1	45	6	94	149	**82**	1	65	70	295
	6500	23	53	4	164	151	**71**	7	73	70	286
RCB LED cluster (637 nm/512 nm/469 nm)	3000	–6	23	2	56	104	**80**	6	73	77	248
	6500	4	25	2	128	118	**76**	9	83	77	228
RGB LED cluster (637 nm/523 nm/452 nm)	3000	17	50	9	80	131	**80**	0	60	67	274
	6500	38	60	10	146	137	**67**	2	65	62	265

Table 3. Colour rendition indices of colour-dulling lamps.

Lamp type	CCT (K)	R_a	CQS	CFI	GAI	GAS	CSI	**CDI**	HDI	LDI	LER (lm/W)
Fluorescent halophosphate	2768	51	54	12	44	74	1	**72**	46	58	(285)
	6333	76	74	26	80	85	0	**53**	38	36	(277)
Daylight pc LED	6042	71	70	17	85	90	4	**53**	50	45	325
Narrow-band YB emitters (446 nm/579 nm and /568 nm	3000	−12	6	3	16	22	2	**81**	71	78	487
for CCT of 3000 K and 6500 K, respectively)	6500	8	4	1	19	20	7	**76**	83	79	397
AGB LED cluster	3000	28	37	12	33	53	1	**67**	49	62	447
(591 nm/523 nm/452 nm)	6500	63	54	24	70	71	0	**51**	43	46	355

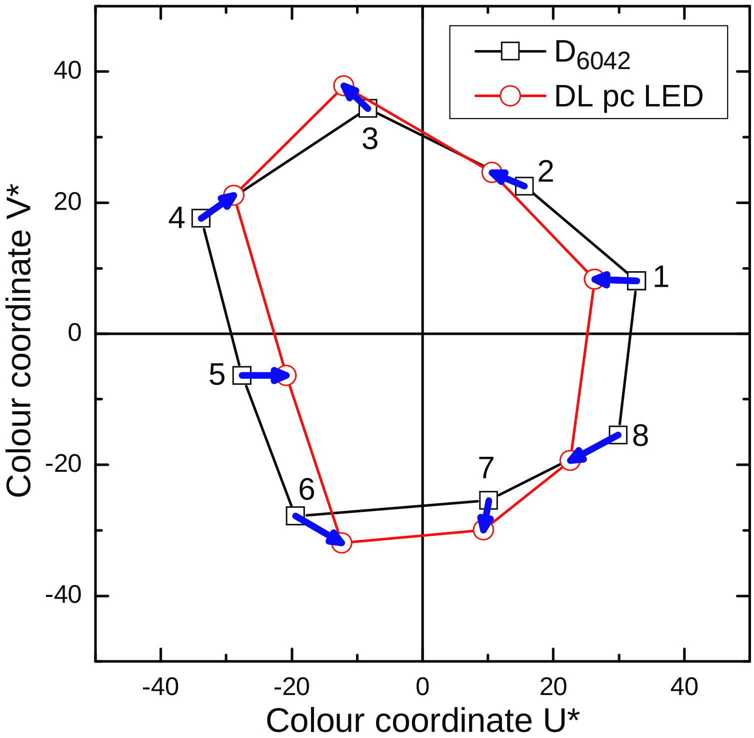

Figure 1. A. Žukauskas *et al*. Colour rendition …

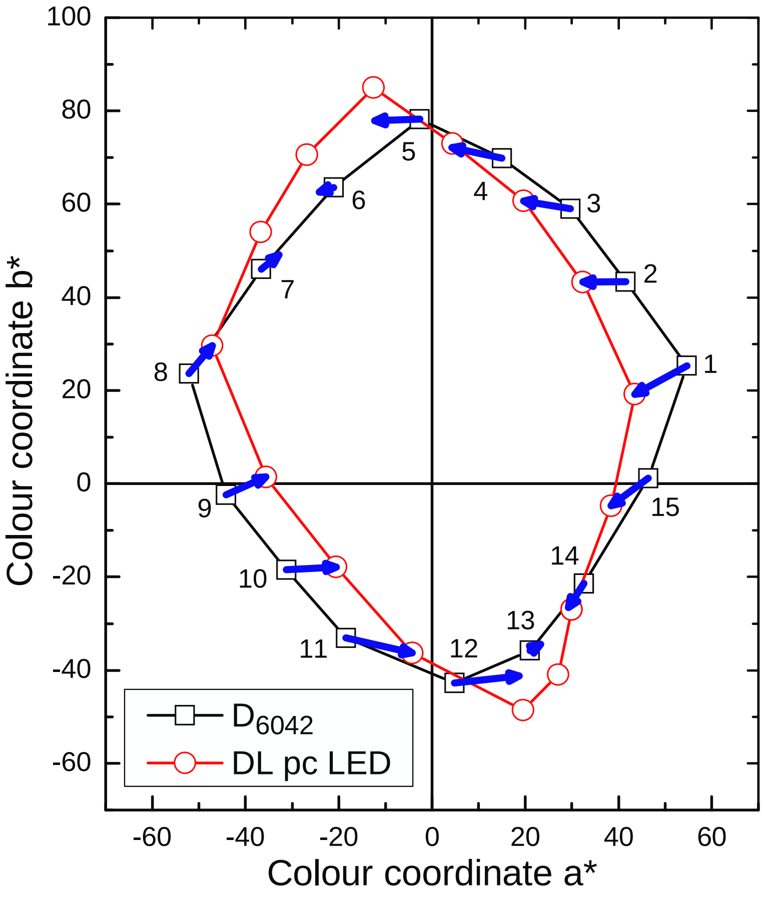

Figure 2. A. Žukauskas *et al*. Colour rendition …

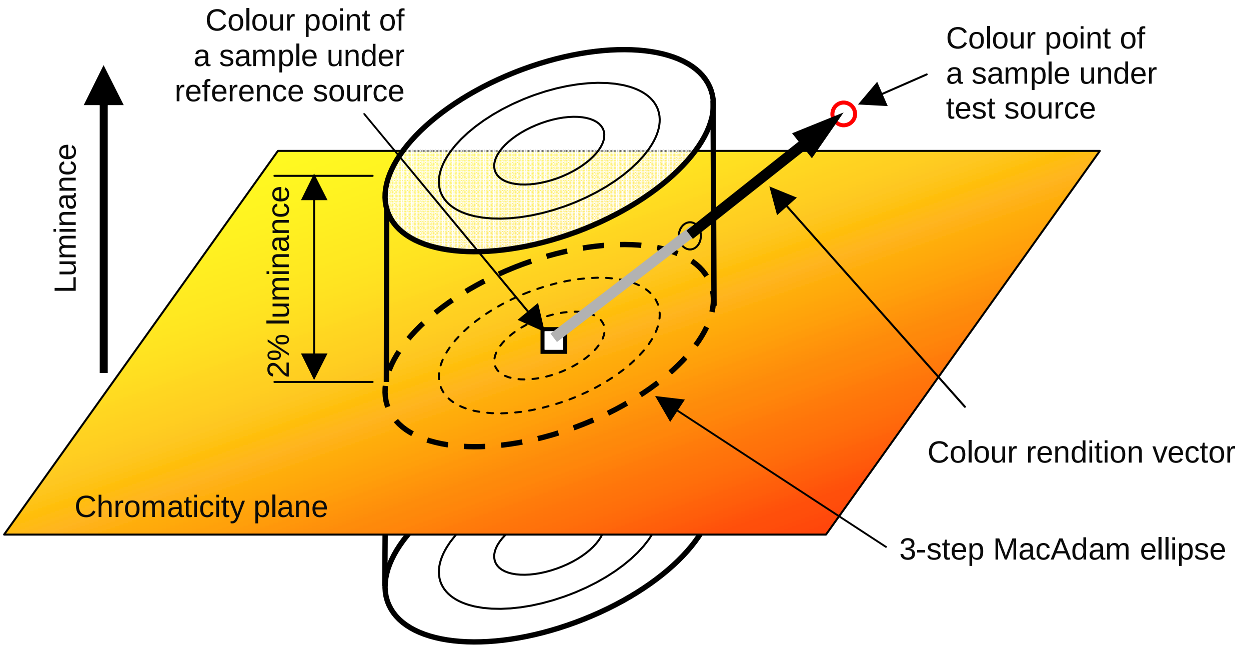

Figure 3. A. Žukauskas *et al*. Colour rendition …

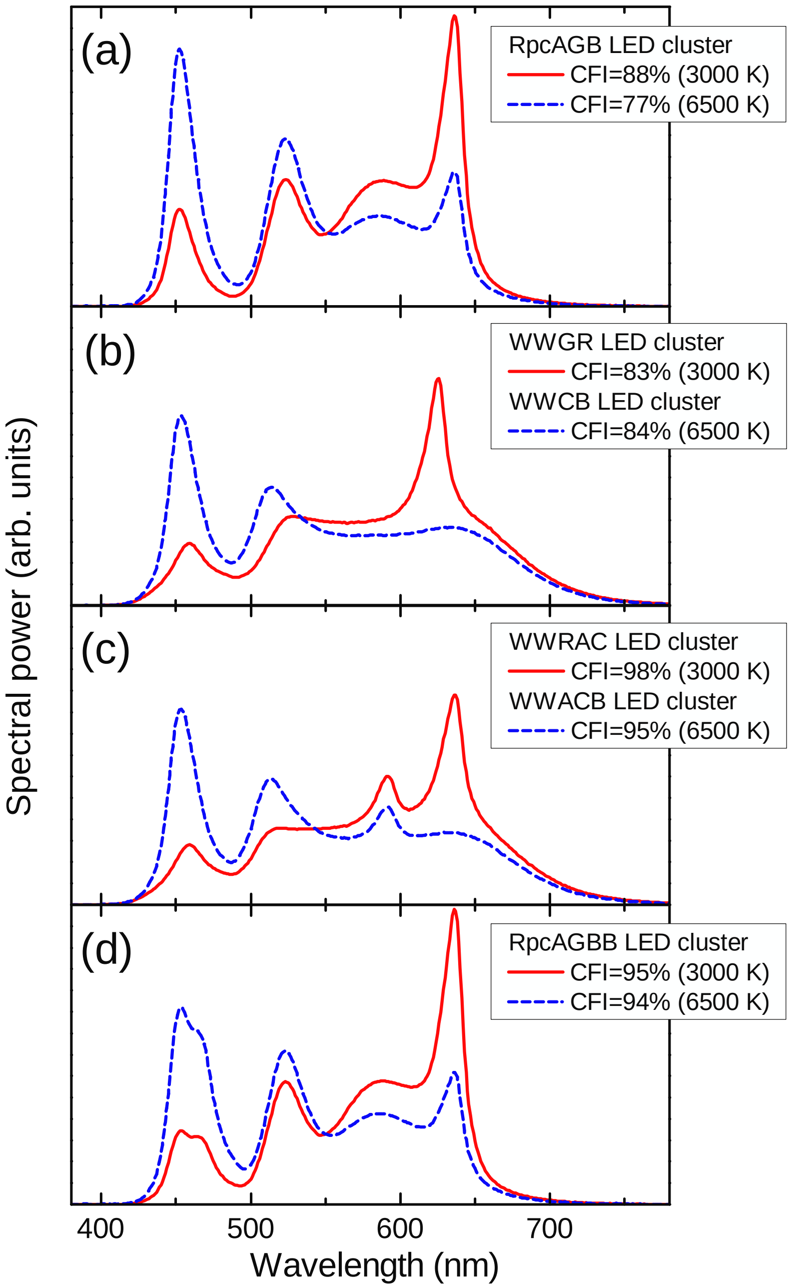

Figure 4. A. Žukauskas *et al*. Colour rendition …

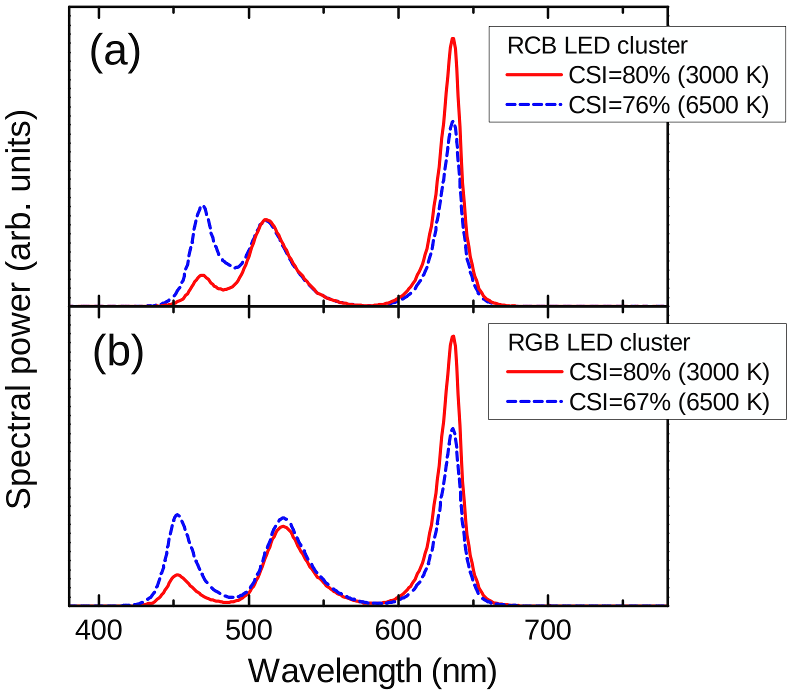

Figure 5. A. Žukauskas *et al.* Colour rendition …

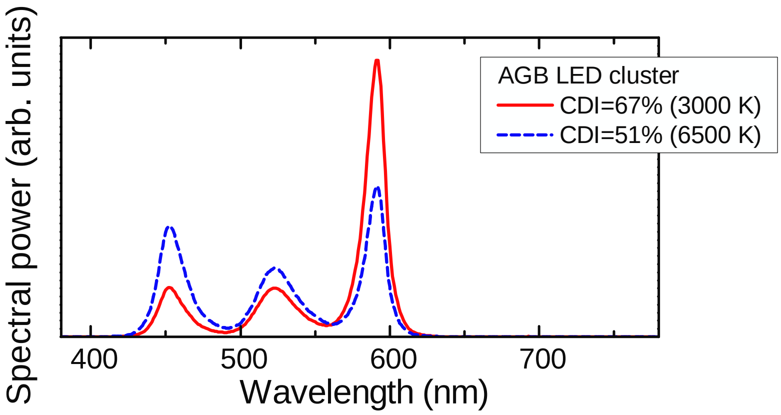

Figure 6. A. Žukauskas *et al.* Colour rendition …