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Polychromatic solid-state lamps versus tungsten radiator: hue changes of Munsell samples

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Abstract
Colour-perception differences under illumination by two quadrichromatic solid-state sources of light have been studied with respect to a tungsten radiator with the same correlated colour temperature (2600 K). A virtual RYgCB source (illuminant), which contains red, yellow–green, cyan and blue components with the line width typical of AlGaInP and AlInGaN light-emitting diodes (LEDs), was fully optimized for the highest value of the general colour-rendering index (CRI) ($R_a = 98.3$). An implemented RAGB source (lamp) contained commercially available red, amber, green and blue LEDs ($R_a = 79.4$). Colorimetric calculations in the Commission Internationale de l'Eclairage 1976 (u', v') colour plane for 40 Munsell colour samples (value 6, chroma/6, hue increment 2.5) revealed the differences in hue discrimination and distortion for both sources in the yellow–green and blue–cyan ranges. These differences were not revealed by the standard analysis of the special CRIs and were lower for the RYgCB illuminant, which contained primary LEDs in the sensitive ranges.
A psychophysical experiment on seven subjects was performed using the RAGB lamp stabilized against thermal and ageing drifts. Despite different colour-perception abilities of the subjects under investigation, the experiment confirmed the calculation results. Methods of obtaining composite white light with high subjective ratings are discussed, based on the obtained data.

1. Introduction

The emerging solid-state lighting emitters based on advanced light-emitting diodes (LEDs) have the potential to substitute conventional sources of light such as incandescent lamps and discharge tubes with considerable gain in efficiency, longevity, robustness and environmental safety [1]. However, injection electroluminescence, which is the mechanism of light generation in LEDs, yields emission within relatively narrow spectral bands. Meanwhile, broadband sources with the ability to correctly reproduce colours of the illuminated objects are required for general lighting. A widely accepted solution is a partial or complete conversion of short-wavelength emission from LEDs using phosphors. An alternative approach is to use sources of white light composed of multiple narrow-band LEDs emitting at different wavelengths. Such multichip polychromatic solid-state lamps offer vast possibilities in lighting with a dynamic control of chromaticity and flux and allow for a trade-off between the quantitative and qualitative properties of light.

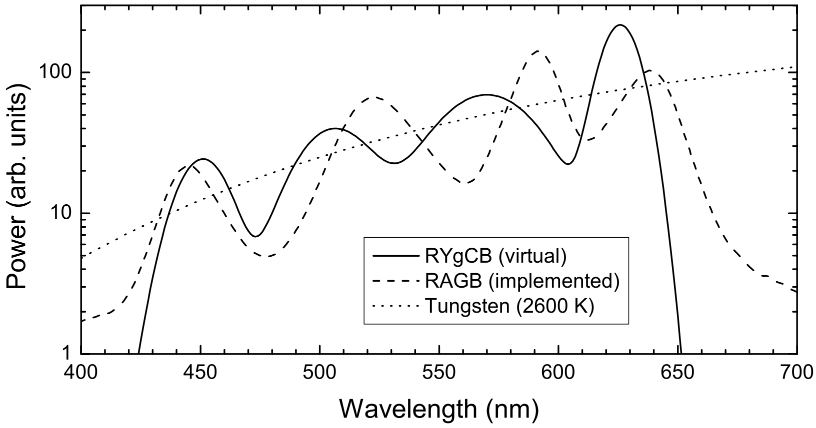

Figure 1. Spectra of the virtual RYgCB illuminant (——) and implemented RAGB quadrichromatic solid-state lamp (– – –), both having the correlated colour temperature of 2600 K. The dotted line shows the spectrum of the tungsten radiator at 2600 K.

The present rating of the quality of white light relies on the general colour-rendering index (CRI), which is calculated using a procedure introduced by Commission Internationale de l'Eclairage (CIE) [2]. This figure of merit is an average of eight special standard indices, which are obtained from the colorimetric shifts for the specified test samples illuminated by a test source and a reference blackbody radiator (the evaluation procedure can be supplemented by six additional indices that use six additional test samples). Although polychromatic lamps composed of four or a larger number of primary LEDs can be optimized for extremely high values of the general CRI [3, 4], this might be insufficient to avoid distorting colours that are different from those of the standard test samples. The reason is that the evaluation procedure is not perfect and the evaluation results for LED-based sources strongly depend on a set of the test samples used [5]. Also, the general CRI is poorly correlated with subjective ratings of colour appearance of various objects under LED lighting [6]. This makes psychophysical experiments on colour perception under solid-state sources very important. However, very few studies of visual perception under solid-state lighting have addressed only the qualitative aspects of this problem [7–9].

In this paper, we report on the characterization of quadrichromatic solid-state lamps in colour rendering for a much larger number of test samples than that used in the standard CIE procedure. The hue distortion of the test samples for two sources with different values of the general CRI is calculated with respect to a tungsten radiator. A psychophysical experiment on the hue perception using an implemented quadrichromatic lamp with stable light parameters is performed and the experimental results are compared with the calculated data.

2. Quadrichromatic sources of white light

The two quadrichromatic sources were compared. The first virtual source (illuminant) was composed of four model LEDs with the peak wavelengths and relative fluxes adjusted for the highest value of the general CRI (R_a). The second implemented source (lamp) was composed of four groups of commercially available LEDs. The lamp delivered a moderate flux of about 250 lm that is comparable to that of

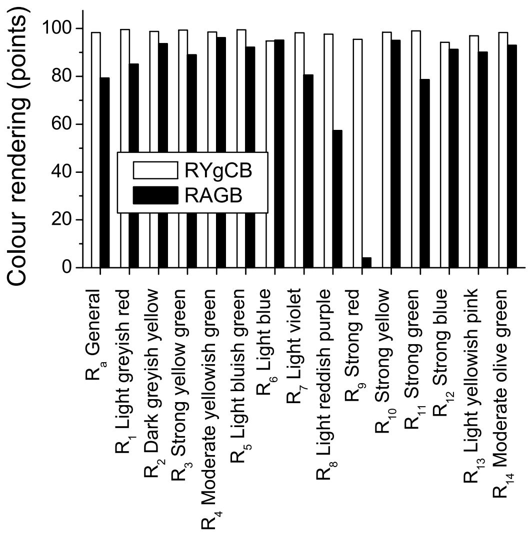

Figure 2. CIE 1995 CRIs for the RYgCB illuminant (□) and RAGB lamp (■) at the correlated colour temperature of 2600 K.

a low-power tungsten radiator (incandescent lamp) with the correlated colour temperature of about 2600 K. To use such a radiator as a reference, the quadrichromatic lamp was tuned to the same correlated colour temperature of 2600 K, which is close to the low-temperature end point of white light.

The spectrum of the virtual source was optimized using a stochastic method [3] and comprised partial contributions of the emission spectra from four primary LEDs with Gaussian shape and line widths typical of AlGaInP (for wavelengths above 570 nm) and AlGaInN (for wavelengths below 570 nm) LEDs [4]. The optimization routine operated in the eight-dimensional space of four peak wavelengths incremented by 1 nm and four relative fluxes incremented by 0.1% that were subjected to three colour-mixing constraints with a predetermined chromaticity of the resulting source. By heuristic variation of the parameters [3], a value of $R_a = 98.3$ was attained for the peak wavelengths of 626 nm (red), 570 nm (yellow–green), 506 nm (cyan) and 451 nm (blue). We call this model source a virtual RYgCB illuminant. The emission spectrum of the RYgCB illuminant is presented in figure 1 by a solid line. Open bars in figure 2 show the general and

14 special CRIs calculated from the emission spectrum using the CIE 1995 procedure [2]. All the special CRIs are seen to have values in excess of 94 points.

The implemented quadrichromatic lamp was designed and fabricated using commercially available high-power LEDs [10]. Since the colours of commercially available LEDs are mostly determined by industry standards for RGB full-colour video displays and signals (such as traffic lights), the available choices of the primary wavelengths are relatively limited. Here we employed the family of 1 W electrical power LUXEON™ emitters (Lumileds Lighting LXHL series) as a set of seven primary sources. For the seven LEDs considered, 18 quadrichromatic sets of the peak wavelengths were found to match the colour-mixing equations for a source that mimics the 2600 K blackbody radiator. Using the LED emission spectra directly measured by a calibrated spectrometer, the highest value of $R_a = 79.4$ was attained by simple searching within the space of the relative fluxes. The resulting white source contained primary LEDs with the emission peaking at 638 nm (red), 594 nm (amber), 523 nm (green) and 441 nm (blue) and was called the RAGB lamp. Because of the non-optimal primary wavelengths, the values of the general CRI and of most of the special indices for the RAGB lamp are well below those for the virtual RYgCB illuminant (figure 2). Of the standard eight indices, the lowest values are for the violet and purple test samples. Among the additional six indices, the strong red test sample has the lowest value (close to zero). The emission spectrum of the RAGB lamp (dashed line in figure 1) differs substantially from that of the fully optimized RYgCB illuminant. Most of the difference is caused by substituting the required yellow–green LED by an amber one. This is accompanied by using the red LED with a longer wavelength and using a green LED instead of a cyan one. Consequently, the spectrum contains wider dips in the yellow–green (540–580 nm) and blue–cyan regions (460–500 nm).

The block structure of the RAGB lamp is shown in figure 3. The fixture contains three to six 1 W LUXEON™ star emitters per primary group (depending on colour) and a photodiode sensor. To avoid colour drift with current, the LEDs are driven by current regulators operating in the pulsed mode at a 150 Hz repetition rate. The duty cycle of the pulses is set by a microcontroller unit programmed via a standard laptop computer. The control unit is equipped with an analogue-to-digital converter that periodically measures the fluxes from each LED group. The measured values are compared with those obtained during the initial calibration and the result is used to adjust the duration of the driving pulses. Such digital

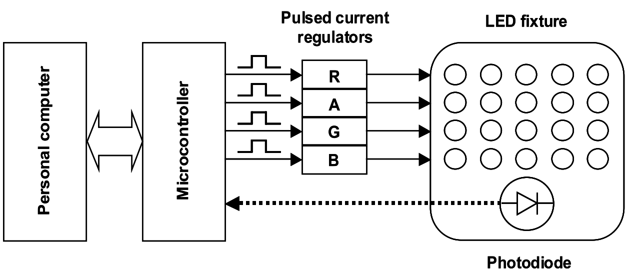

Figure 3. Block diagram of the implemented RAGB quadrichromatic lamp.

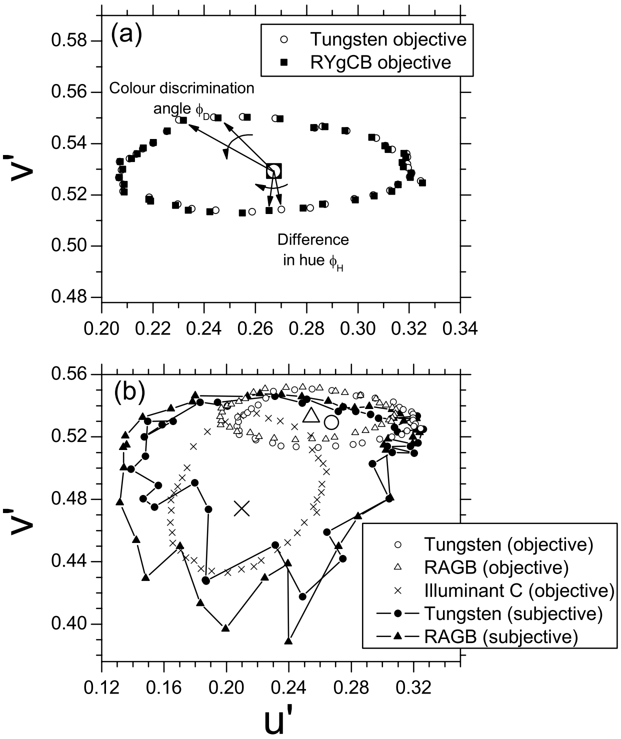

Figure 4. (*a*) Segment of the CIE 1976 (u', v') colour plane with the objective chromaticity coordinates of 40 Munsell samples (value 6 and chroma/6) illuminated by the tungsten radiator at 2600 K correlated colour temperature (○) and the mimic RYgCB illuminant (■). The discrimination angle for the tungsten radiator and difference in hue between the tungsten radiator and RYgCB illuminant are indicated. (*b*) Larger segment of the (u', v') colour plane with the chromaticity coordinates of the same Munsell samples determined by subject 'RS' under illumination by the tungsten radiator (●) and RAGB lamp (▲), respectively. Also shown are the elliptic loci of the objective (calculated) chromaticity coordinates for the tungsten radiator (○), RAGB lamp (△) and standard illuminant C (×). The central points (enlarged) in each objective ellipse refer to the Munsell neutral sample N6.

feedback allows for high stability of the chromaticity and flux with respect to thermal and ageing drifts of the primary LED output [7].

3. Stimuli and objective distortions of hue

The colour order system used in the study is the Munsell system, originated by the artist A H Munsell in 1905 and later extended and refined [11, 12]. This most popular system scales colours in hue, chroma (saturation) and lightness by uniformly spacing them in accordance with the perception of an observer with normal colour vision [13]. Forty Munsell colour samples of value 6 (same as that used in the CIE method for the estimation of the general CRI [2]), chroma/6 (the average quantity used in the CIE method) and hue incremented by 2.5 (the confident limit for discrimination of perceived hues) were used [14]. Figure 4(*a*) depicts the calculated (objective) chromaticity coordinates of the samples under illumination with the tungsten radiator and RYgCB illuminant plotted over a segment of the CIE 1976 (u', v') colour plane. The CIE 1976 (u', v') colour plane was used in the calculations since the distances between colour points in this presentation have a good match with the subjective discrimination of colours. Each group of the 40 coordinates is seen to reside within elliptical contours with the centres corresponding to the Munsell neutral sample N6. Of 40 samples, 32 can be characterized by the dominant wavelengths ranging from 449 nm (blue sample) to 635 nm (red sample). For specificity, the dominant wavelength of the samples was determined under standard illuminant C (the averaged spectrum of 'direct sunlight' specified by the CIE), which the Munsell palette is based on [13], by drawing a vector from the central point to the chromaticity point of the sample (crosses in figure 4(*b*)) and using the vector extension of the locus of the monochromatic points (not shown in figure 4). The remaining eight 'purple' samples have no dominant wavelengths and are characterized by the complementary wavelengths, which are the dominant wavelengths of the samples on the opposite side of the corresponding ellipse. Here, the complementary wavelengths range from 495 nm (red–purple sample) to 567 nm (blue–purple sample).

Figure 4(*a*) also defines the colorimetric characteristics under investigation. Here we refer to the colorimetric angular characteristics ϕ_D and ϕ_H, which reflect the vision sensitivity to the hue distortion. One of these characteristics is the hue discrimination angle, ϕ_D^α, which is the angle between the radii connecting the chromaticity points of neighbouring Munsell samples with that of the central neutral sample under a given source α. Another characteristic is the hue difference, $\phi_H^{\beta:\gamma}$, which is the angle between the radii relative to the chromaticity points of a given sample obtained under two different sources β and γ.

The (u', v') chromaticity coordinates of the samples under the tungsten radiator, RYgCB illuminant and RAGB lamp were calculated and the relative differences in hue discrimination between the tungsten radiator (W) and RYgCB illuminant, $(\phi_D^{RYgCB} - \phi_D^W)/\phi_D^W$ (figure 5(*b*)), as well as between the tungsten radiator and RAGB lamp, $(\phi_D^{RAGB} - \phi_D^W)/\phi_D^W$ (figure 5(*c*)), were estimated. Also the corresponding relative objective differences in hue, $\phi_H^{RYgCB:W}/\phi_D^W$ (figure 5(*e*)) and $\phi_H^{RAGB:W}/\phi_D^W$ (figure 5(*f*)), were determined. As one can see from figure 5, objective hue distortions for both the RYgCB illuminant and RAGB lamp occur in the yellow–green (dominant wavelength 560–600 nm) and blue–cyan (470–500 nm) regions as well as in the purple region around the same values of the complementary wavelengths. The completely optimized RYgCB illuminant exhibits smaller hue distortions than the implemented RAGB lamp. However, these colorimetric characteristics are in poor correlation with the special CRIs (figure 2), which predict poor colour rendering for purple (R_8) and especially strong red (R_9) colours and show rather high values of indices for yellow–green (R_2 and R_3) and blue–cyan (R_5) indices. Such a discrepancy is probably due to the different approaches used in this work, where emphasis is laid on hue, and in the CIE 1995 procedure, where differences in lightness and saturation (the radial colorimetric shift) play a major role. In other words, our results imply that hue distortions, which are known to be the most important in colour discrimination [15], are heavily underestimated in the CIE 1995 procedure.

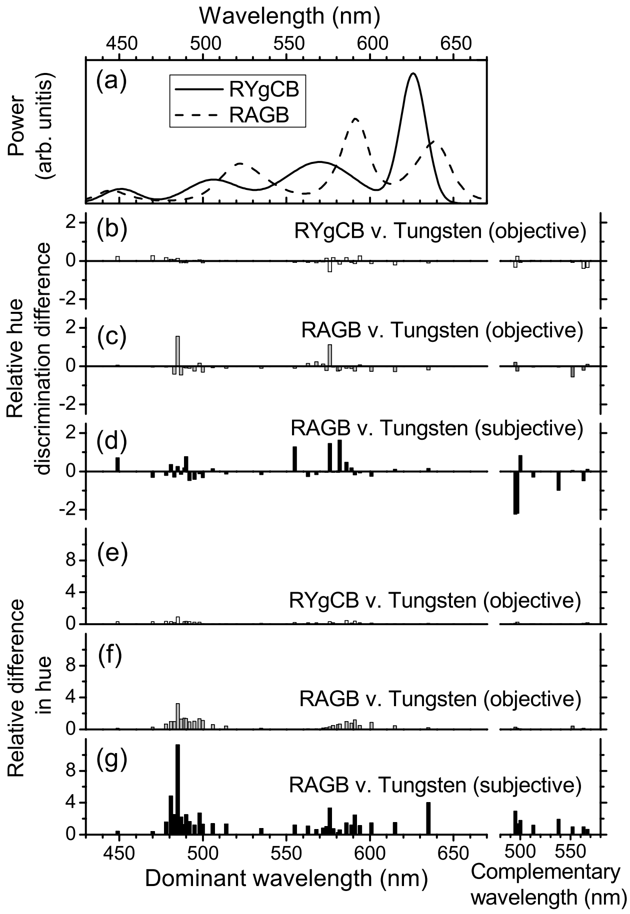

Figure 5. (*a*) Spectra of the virtual RYgCB illuminant (——) and implemented RAGB lamp (– – –) with the correlated colour temperature of 2600 K. Calculated (objective) relative hue discrimination differences for the Munsell samples under RYgCB illuminant versus tungsten radiator (*b*) and RAGB lamp versus tungsten radiator (*c*); subjective relative hue discrimination differences under the RAGB lamp versus tungsten radiator (*d*). Calculated (objective) relative differences in hue for the Munsell samples under the RYgCB illuminant versus tungsten radiator (*e*) and RAGB lamp versus tungsten radiator (*f*); subjective relative differences in hue under the RAGB lamp versus tungsten radiator (*g*). The results of the psychophysical experiment are averaged over seven subjects. (*b*)–(*g*) left, 32 Munsell samples characterized by the dominant wavelength; right, 8 'purple' samples characterized by the complementary wavelength.

4. Psychophysical experiment

The psychophysical experiment was carried out in a dark room containing a cabinet for the Munsell samples and a computer-driven colour monitor. The cabinet, of dimensions 50 cm × 50 cm × 50 cm, was equipped with either the RAGB lamp or tungsten radiator installed on the ceiling. The Munsell samples were put on a pedestal placed at the bottom of the cabinet. The pedestal was inclined towards the subject and illuminated by a lamp. The inside of the cabinet was coated with light grey paper to maintain smooth background illumination. The subject viewed the stimuli at an angle of 3.4° by 3.4°. A spectrometrically calibrated colour CRT monitor (Philips Brilliance 201CS) was used as a reference. A stimulus displayed on the monitor had the same angular size as that in the chamber. The hue, saturation and lightness of the stimulus were software-controlled using a keyboard.

Seven subjects with normal trichromatic colour vision (checked using the Farnsworth–Munsell 100-hue test) and with normal or corrected to normal visual acuity participated in the experiment. During the experiment, a subject looked at an illuminated Munsell sample within the cabinet and matched the colour of the stimuli displayed on the monitor with that of the sample. (Before the experiments, the subjects had been adapted to the cabinet light source in order to avoid long-lasting adaptation to the monitor and, during the experiments, were continuously readapted.) In this way, all 40 Munsell samples were run over and the acquired colour settings of the monitor were recorded as the perceived chromaticities. After a trial with the RAGB lamp, the experiment was repeated with the tungsten radiator.

Filled points in figure 4(*b*) show the results of the psychophysical experiment for one observer, chosen as typical, and known as 'RS'. One can see that the subjective chromaticity points obtained for both the tungsten radiator (filled circles) and the RAGB lamp (filled triangles) are remarkably shifted away from those calculated (open circles and triangles, respectively). The shift of the contours, which clearly mimic the locus of the chromaticity points under standard illuminant C (crosses), is due to the effect of colour constancy, which is due to a striving of the human vision to perceive a colour under a given source of light as being the same as under sunlight. The essential outcome of the experiments performed is that different subjects exhibited different chromaticity shifts of the perceived colours owing to their different abilities in colour-constant perception. However, the angular characteristics of the chromaticity shifts, which refer to hue distortions, were very similar for all the subjects.

Figure 5(*d*) shows the relative hue discrimination differences of the RAGB lamp versus the tungsten radiator averaged over seven subjects. The subjective differences agree with but are larger than the calculated (objective) ones (figure 5(*c*)). These larger values can be attributed to inhomogeneity of the colour space used and to experimental uncertainties. The averaged subjective differences in hue (figure 5(*g*)) exhibit a similar behaviour when compared with the objective differences (figure 5(*f*)). Once again, both the hue discrimination difference and hue distortion are the largest in the yellow–green (dominant wavelength 560–600 nm) and blue–cyan (470–500 nm) regions and mirror purple regions. The subjective relative hue mismatch in these regions is so high (330% and 1100% for yellow and cyan samples, respectively) that the subjects definitely perceived wrong colours. Meanwhile, the special CRIs reveal distortions mainly in the purple region (R_7 and R_8, figure 2), where the subjective relative hue difference amounts to 300% and 100% for red–purple and blue–purple colours, respectively.

5. Discussion

It should be noted that the yellow–green and blue–cyan regions, where both the objective and subjective distortions of the hue are the highest, correspond to the ranges of the dominant wavelengths with the highest density of the Munsell samples (see figure 5), i.e. where human hue discrimination is highest. Note that these regions are exactly between the peaks of the spectral functions of the retinal receptors [13], where the derivatives of the functions are large and sensitivity of visual perception to spectral variations is high.

Therefore, we suggest that the spectra of polychromatic sources of white light should contain intense and smooth components in the 560–600 nm and 470–500 nm ranges in order to avoid the hue distortions. (For most typical objects under artificial illumination, the former yellow range is more important.) This seems to be in contrast to a widely accepted notion that high colour-rendering properties of composite white light rely on primary sources with the spectral peaks at 450, 540 and 610 nm and that the wavelengths near 500 and 580 nm should be avoided [16]. While the 450, 540 and 610 nm wavelengths are important for three-component white light, our observations indicate that this might not be true for light composed of a larger number of primary sources. In particular, we expect that a quintichromatic red–yellow–green–cyan–blue (RYGCB) solid-state lamp [3, 17] should be the most favourable polychromatic source of white light with the general CRI maximized and hue distortions minimized.

A further development of multichip solid-state lamps depends on the availability of yellow–green and cyan LEDs. While the cyan AlGaInN LEDs in the 500 nm range are already available, the materials and technological issues related to fabrication of efficient LEDs in the yellow–green spectral region, which is at the crossover between the AlInGaN and AlInGaP technologies [18], remain unresolved. The problem could be mitigated by developing coloured LEDs with complete phosphor conversion [19] or through the use of a complementary approach, which employs white phosphor-converted LEDs containing a yellow band in combination with narrow-band coloured LEDs [20].

6. Conclusions

Virtual RYgCB illuminant and implemented stabilized RAGB solid-state quadrichromatic lamp were compared with a tungsten radiator in terms of the hue distortion. The hue discrimination differences and the differences in hue calculated in the CIE 1976 (u', v') colour plane for 40 standard Munsell samples revealed hue distortions in the yellow–green (560–600 nm) and blue–cyan (470–500 nm) ranges of the dominant wavelength as well as in the mirror blue–purple and red–purple ranges. The standard analysis based on special CRIs misses the hue distortions in the yellow–green and blue–cyan regions. These distortions were considerably lower for the RYgCB illuminant that contained components which peaked at 570 and 506 nm compared with those for the RAGB lamp. A psychophysical experiment with the Munsell samples illuminated by the RAGB lamp validated the results of colorimetric calculations despite different colour-perception abilities of the subjects under investigation.

Our results imply that white light quality rating based on CIE 1995 procedure overestimates the importance of the overall colorimetric shifts and underestimates the importance of the hue distortions. Therefore, this standard rating procedure should be revised. We suggest that composite white light with high subjective rating of illumination, is the light optimized in terms of both colorimetric shifts and hue distortions. This can be achieved by using components both at the peaks of the retinal-receptor spectral functions (red, green and blue) and in the in-between yellow–green and blue–cyan regions, respectively. Lamps providing such white light (e.g. quintichromatic sources) can be implemented based on a variety of primary sources offered by solid-state technology.

Acknowledgments

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