Luminance-Brightness Discrepancy in Near White Lights

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Abstract

The present study introduces interesting disagreement phenomena between luminance and brightness in near white colors reproduced using LEDs. Target stimuli having identical luminance and chrominance (CCT) appeared to have different brightness. Observers tended to choose brighter one from the two target stimuli in contrary fashion. The relative quantities of the ipRGC (intrinsically photosensitive retinal ganglion cells), S-cones, and rods were compared over the stimuli besides the luminance, i.e., photometric quantity. An apparent reason for the discrepancy could not be revealed in this study; however it could be induced that the contribution of S-cone, rod, and ipRGC (circadian) photosensitive receptors as well as L- and M-cones to the brightness perception causes the discrepancy results.

Review of the current knowledge on brightness-luminance discrepancy

The brightness-luminance disagreement was first observed against colored stimuli. Red, green and blue surfaces tend to appear brighter than equal-luminance white or yellow surface. The CIE published a comprehensive bibliography on brightness-luminance discrepancy [1]. Brightness is a non-additive quantity. The additive mixture of two stimuli of different chromaticity but the same luminance does not look to have the brightness corresponding to the twofold luminance of one of the stimuli. Thus, brightness visibility function can be described only for monochromatic stimuli [2]. Sagawa has built an empirical model that describes well brightness perception of surface colors in a wide luminance range [3]. A further empirical model correcting luminance to brightness for colored lights mostly reproduced on color displays has been elaborated by Covan and Ware [4].

The brightness-luminance discrepancy phenomena were also observed for near white colors. Alman investigated the influence of Corresponding Color Temperature (CCT) on brightness perception and learnt that the brightness to luminance ratio (B/L) for the CIE Illuminant D65 and A was 1.35 [5]. Berman found that the scotopic luminance could be an important factor in the brightness perception [6, 7]. Fotios and Levermore attempted to figure out the impact of changes in the CCT and Color Rendering Index (CRI) on the B/L ratio using a large number of light sources in viewing booths [8]. Afterwards, Fotios computed the correlation coefficients between the subjective brightness data and model predictions: 0.36, 0.89, 0.74, and 0.52 in relation to CCT, CRI, gamut area, and the Ware-Covan correction [9]. Vienot and co-authors suggested that the intrinsic photosensitive Retinal Ganglion Cell (ipRGC) and its role in the pupil diameter adjustment might affect the brightness perception [10]. On the other hand, Fotios showed that the pupil size changes had no influence on the brightness perception [11].

There are three general methods to determine brightness-luminance relationship: side-by-side comparison, rapid alteration, and subjective scaling. These three methods were examined in detail by Fotios [12, 13]. One of his findings was that higher CCT lamp looked brighter in the side-by-side comparison, but this was not the case in the subjective scaling. Then, chromatic adaptation was considered to be a feasible reason for the different observation result. The chromatic adaptation has two phases: short-term and long-term adaptations lasting for approximately 5 (probably, incomplete) and 60 (complete) seconds. A mixed adaptation probably takes place in the side-by-side observation while almost complete adaptation in the subjective scaling case. Observers are likely merged into the lit scene in subjective scaling. The rapid alteration may permit only the first phase of re-adaptation. The conclusion made by the authors was that the side-by-side comparison can be the most appropriate to find out the brightness-luminance relation given that the mixed adaptation is usually encountered in real life.

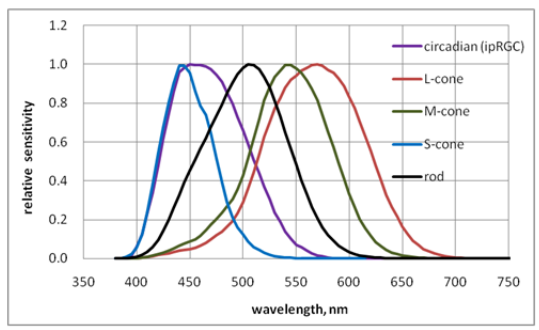

Figure 1. *The relative spectral sensitivity functions of the cone fundamentals (LMS), the rods, and the ipRGCs (circadian action function according to Gall's estimate [14]).*

The difference between brightness and luminance seems to be a well established phenomenon. The various causes were suggested by many research groups. Some suppose chromatic influence and others try to explain it with rod or S-cone contribution. Nowadays, the ipRGC is also taken into account in describing the brightness-luminance discrepancy [10]. The present study therefore attempted to further investigate the discrepancy phenomena over the near-white LED stimuli having the identical luminance and chrominance (CCT) values. Before the experiments, the relative spectral sensitivities of the photosensitive receptors of S-cone, rod, and ipRGC (circadian) as well as L- and M-cones were compared. These are shown in Figure 1. Then, the LED target stimuli having peaks at different short wavelengths were selected in order to figure out the influence of the S-cone, rod, and ipRGC on the brightness-luminance disagreement.

Experiments and Results

A tuneable white LED vs. cyan and red LED

The brightness and luminance comparison experiments were carried out in observation booths. An LED light source was installed in an upper compartment of the booth. The lower compartment was painted black to avoid unwanted reflections. Non-fluorescent white papers were placed at the bottom of the booth and so could be illuminated by the light source. Figure 2 shows a viewing example in the booth.

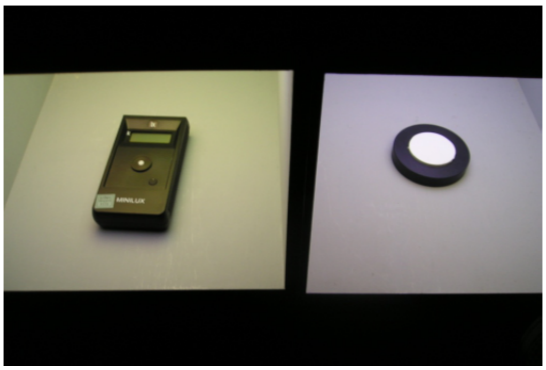

Figure 2. *The near white appearance in the non-fluorescent papers viewed in the viewing booths: an illuminance meter in the left booth and a white diffuse PTEF reference in the right booth.*

A tunable white light LED source (Zumtobel experimental luminaire) and cyan + red LED panel were located in each of the double booths. The controllable range in the CCT in the tunable white LED was 3000 – 7000 K. The SPDs of the two LED sources are illustrated in Figure 3. The peaks in the short wavelength range in these two sources are remote, i.e., far from each other. Hence, the impact of the excitation differences between the S-cone and the ipRGC (shown in Figure 1) on the brightness-luminance discrepancy could be manifested. The current of the two LED sources was adjusted using a iDrive Force 24 multi-channel power supply by means of an MBNLED RGB DMX driver software. The currents applied to the two LED sources in both booths were changed until the same luminance and chromaticity of about 100 cd/m^2, and x=0.4, y=0.4 were obtained against a white diffuse PTEF reference. Observers were firstly asked to compare the brightness from the reflected lights of the non-fluorescent white paper placed at the bottom of each booth. The 2nd task was in turn to modify the luminance of the cyan+red LED panel by changing the LED currents parallel without altering its CCT in order to perceive identical brightness relative to the other LED source.

Twenty-five observers participated in the visual experiment. Three of them were younger than 35 years old and nine were older than 65 years old. The brightness-comparison experiment results are summarized in Table 1. Four observers found the cyan+red LED panel looking brighter than the other white LED source. Hence, 14 % lower luminance value was set for the cyan+red LED compared with the white LED. The inter-observer variability was only ± 2 %. The greater part of the observers perceived brighter appearance in the white LED booth and so 20 ± 10 % higher luminance value was applied for the cyan+red LED. Equal brightness within a ± 3 % range, which probably fell into the intra-observer variability, was viewed by the rest six observers. No age dependence was revealed in the experiment.

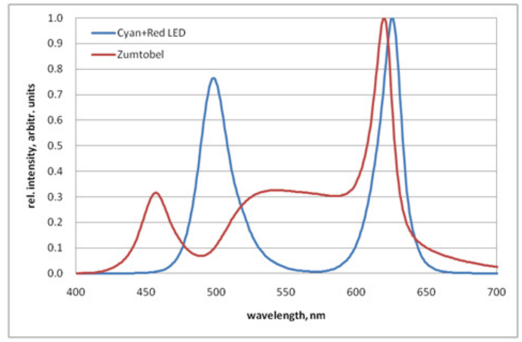

Figure 3. *The spectral power distributions of the cyan+red LED and the Zumtobel white LED.*

Table 1: The brightness-luminance comparison experiment results in the case of the tuneable white LED vs. the cyan+red LED panel (2 LED).

Number of observers (an age group)	4 (1 ≤ 35 years 36 < 3 < 65)	15 (1 ≤ 35, 4 ≥ 65 36 < 10 < 65)	6 (1 ≤ 35, 1 ≥ 65 36 < 4 < 65)
Relative luminance 2 LED / Zumtobel LED	0.86	1.20	1.02
% standard deviation	2.1	9.9	3.1

The relative quantities were computed using Eq. (1) to examine the influence of different SPDs especially in short wavelengths for the two LED sources on the luminance-brightness discrepancy results.

$$\frac{\int_{380}^{780} S(\lambda)x(\lambda)d\lambda}{\int_{380}^{780} S(\lambda)V(\lambda)d\lambda} \qquad (1)$$

where S(λ) is the spectral power distribution in each of the cyan+red LED panel and Zumtobel white LED, x(λ) is the spectral sensitivity function of S-cone S(λ), rod V'(λ), or ipRGC (C(λ), circadian action function according to Gall's estimate [14]), and V(λ) is the spectral luminosity function.

Table 2 describes the computed relative quantities of the S-cone S(λ), rod V'(λ), and ipRGC (C(λ)) compared to the luminosity function in the photopic vision (V(λ)) for the cyan+red LED and white LED sources. The circadian C(λ), S-cone S(λ) and rod V'(λ) photosensitive receptors have different peaks in the blue portion of the visible spectrum (see Figure 1). This is expected to cause different respective quantities of the S-cone, rod, and ipRGC (circadian) compared to the luminosity function (V(λ)) in each of two LED sources. The computation results in Table 2 demonstrate this hypothesis, i.e., three distinctively different values in each LED source. As shown in Figure 3, there is an apparent deviation in the peak spectral responses at short wavelengths between the cyan+red LED panel and the Zumtobel white LED. Due to this fact, the different quantity ratios between C(λ)/V(λ) and V'(λ)/V(λ) that calculated against the SPDs of the two LED sources are found in Table 2.

Table 2: The relative quantities in the S-cone S(λ), rod V'(λ), and ipRGC (C(λ)) compared to the luminance (V(λ)) for the tuneable white LED and the cyan+red LED panel.

LED source	C(λ)/V(λ) (circadian)	S(λ)/V(λ) (S-cone)	V'(λ)/V(λ) (rod)
cyan+red	0.73	0.22	1.1
Zumtobel white	0.39	0.23	0.56

5-peaks LED vs. cyan and red LED

It was attempted to verify the luminance-brightness discrepancy phenomena observed in the previous section by replacing the Zumtobel white LED with another LED source having five peaks at 450, 520, 593, 626, and 650 nm. The SPDs of the two LED sources are shown in Figure 4. The two LED sources were firstly set to produce the same illuminance of 472 lx ± 4.8 % and the same correlated color temperature of 3300 K. Twenty-four observers were then requested to control the luminance of the cyan+red LED panel to be viewed to have equal brightness by comparison with the other LED source having five peaks. Only three of them took part in both 1st (described in the previous section) and 2nd experiments. Again, the disagreement tendency between luminance and brightness was found. The observation results can be separated into three groups and are described in Table 3.

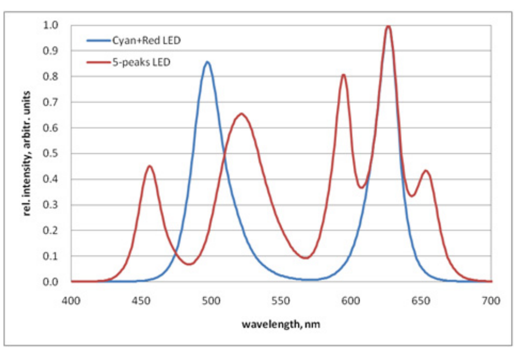

Figure 4. *The spectral power distributions of the cyan+red LED and the LED having five peaks at 450, 520, 593, 626, and 650 nm.*

The red+cyan LED panel looked brighter and so the five observers decreased its luminance about 18 % less from the initial value. The largest number (15) of observers increased the luminance of the red+cyan LED by about 46 % higher from the first setting owing to darker appearance in that LED against the five-peaks LED. The largest scattering in the adjusted luminance values is however noticed in this observation group, i.e., ± 32 % inter-observer variability. Four observers perceived almost identical brightness. Despite the fact that the adjusted chromaticity was very near to the Planckian locus, some observers found the white paper to be slightly colored. The 15 observers who raised the luminance of the red+cyan LED made remarks about the slightly yellowish appearance in that LED whereas the five observers who decreased its luminance noticed greenish appearance. An in-depth analysis for these remarks should be followed.

Table 3: The brightness-comparison experiment results in the case of the 5-peaks LED vs. the cyan+red LED panel (2 LED).

Number of observers	5	15	4
Relative luminance 2 LED / 5-peaks LED	0.82	1.46	1.0
% standard deviation	7	32	4

The same computation was made using Eq. (1) for the two LED sources in the 2nd experiment. The calculated relative quantities are described in Table 4. The same trends discovered in Table 2 are again observed: three different ratios according to the three different photosensitive receptors in each LED source, and also different ratios between C(λ)/V(λ) and V'(λ)/V(λ) for the cyan+red LED and five-peaks LED.

Table 4: The relative quantities in the S-cone S(λ), rod V'(λ), and ipRGC (C(λ)) compared to the luminance (V(λ)) for the 5-peaks LED and the cyan+red LED panel.

LED source	C(λ)/V(λ) (circadian)	S(λ)/V(λ) (S-cone)	V'(λ)/V(λ) (rod)
cyan+red	0.78	0.25	1.12
5-peaks LED	0.46	0.24	0.69

Discussions

All two experiments showed the same trends. The LED lighting sources that have the same luminance and chrominance values appeared to have deviated brightness. Additionally, the brightness-luminance discrepancy phenomena were noticed in different manners according to the observers. The majority of observers viewed darker appearance in the cyan+red LED than the Zumtobel white LED and the 5-peaks LED (15 observers in each of tables 1 and 3). Thus, they increased the luminance of the cyan+red LED until equal brightness was seen against the other LED source.

The peak spectral responses in the blue portion for the Zumtobel white LED and the 5-peaks LED are located at shorter wavelengths than for the cyan+red LED (see figures 3 and 4). The peak of the S-cone S(λ) is placed at shorter wavelengths than that of each of circadian C(λ) and rod V'(λ). Final input in the blue portion delivered to visual neural connections is expected to be formed mainly through the S-cone sensitivity function in the Zumtobel white LED and the 5-peaks LED, but through the circadian C(λ) and rod V'(λ) functions in the cyan+red LED. This can probably lead to the different quantity ratios between C(λ)/V(λ) and V'(λ)/V(λ) for the cyan+red LED and the Zumtobel white LED in Table 2 (and for the cyan+red LED and the 5-peaks LED in Table 4), furthermore different brightness perception.

Conclusions

The luminance-brightness discrepancy phenomena were found in near white LED stimuli that had different spectral power distributions in the visible wavelengths, but had identical luminance and chrominance (CCT) values. These results were interestingly found differently according to the observers. The first observation group perceived equal brightness, i.e., agreement between luminance and brightness. The second group viewed brighter appearance for the stimuli having shorter wavelength radiation in the blue portion of the visible spectrum whereas the remaining group observed darker appearance. Within the experimental conditions observed in this study, the most observers perceived brighter appearance in the near white LED stimuli having peaks in the blue portion at shorter wavelengths. Considering that L- and M-cone photoreceptors mostly contribute to the luminance, brightness-luminance disagreement results can probably therefore occur by the contribution of the photosensitive receptors of S-cone, rod, and ipRGC (circadian) as well as L- and M-cones. However, further investigations are needed to find out apparent causes of the discrepancy results between luminance and brightness in the near white colors having equal luminance and chrominance.

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Author Biography

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