

Space of visual and circadian parameters of RGBW lighting systems

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Abstract - Due to the proven effect of light on human circadian rhythms, nowadays researchers and developers of lighting systems (LS) concentrate on the non-visual parameters of light and methods of ensuring a safe comfortable light environment. This requires optimisation of spectral power distribution (SPD). In this view the most promising and functional are RGBW systems due to their ability to change dynamically SPD and, hence, light parameters. In this work we explore two RGBW (red-green-blue-white) systems with different white LEDs (warm white and neutral white) and the space of visual and non-visual parameters that they can ensure. Visual parameters are studied in terms of colour rendering index, colour fidelity index and visual corneal illuminance while non-visual parameters are studied in terms of circadian light, circadian stimulus and circadian action factor. These parameters are calculated for different contribution of the components in a correlated colour temperature (CCT) range of 2500 – 7000K. In addition, acceptable criterion of the colour fidelity index above 85 is used. It is shown that under this condition the circadian action factor in the range of 0.33-0.98 can be obtained by changing the CCT and (or) colour fidelity index. Also an achievable area of the circadian stimulus versus corneal illuminance space for RGBW systems is found. It enables to choose optimal combination of CCT, circadian stimulus and corneal illuminance to provide the desired level of circadian effect with sufficient visual comfort depending on the daytime and field of system's implementation. This data is useful for LS manufacturers and lighting designers to create a comfortable lighting environment.

Keywords - RGBW colour mixing, tunable white light, circadian effect, colour rendering, colour fidelity index.

I. INTRODUCTION

The non-visual impact of light on human, its productivity, well-being and health is already proven [1-3]. Over the past few decades, a study of this influence, its nature and assessment methods have been actively conducted [4-8]. The rapid development of this field is associated with the discovery of photosensitive Retinal Ganglion Cells (ipRGCs) being signal transmitter to the suprachiasmatic nucleus that is responsible for the circadian rhythm of humans through the hormone

melatonin secretion [9-12]. Nocturnal melatonin suppression is an endocrine disruptor and can lead to fatigue, diabetes, obesity and other diseases, even to cancer [13, 14]. Therefore, it is important to continue studying the impact of light on human and take into account this impact when creating light environment.

Analysis of the ipRGCs and melatonin secretion sensitivities to different wavelengths showed that the human circadian system and visual system have different sensitivity functions. The first one has sensitivity peak in the blue spectral region and the second one – in the green region for photopic vision (555nm). The first model of circadian spectral sensitivity was proposed by Gall et al. [15] and its maximum is in the range of 445 – 465 nm. Later Rea et al. [16] proposed a more accurate model which is based on the retina's neurophysiology and neuroanatomy, and takes into account studies [10, 17] of nocturnal melatonin suppression caused by light with different spectral power distributions (SPDs). According to the data, there are three main parameters for evaluating the circadian effect of light sources. They include (i) the circadian light CL_A being an analogue of visual illuminance, related (ii) circadian stimulus CS [11, 18] being the percentage of melatonin suppression for an hour exposure, as well as (iii) circadian action factor acv representing the ratio of circadian and visual stimulus. All these parameters are affected predominantly by the SPD, while CL_A and CS are also affected by the visual corneal illuminance and time. At the same time, important parameters of visual perception of light are colour rendering and correlated colour temperature (CCT) [19, 20]. Today, more attention is paid to these visual parameters and luminous efficacy when developing and choosing lighting systems. But due to the difference in the visual and non-visual perception of light, developers and designers have to take into account both types of parameters to create comfortable lighting environment. And the main benchmark is the similarity of the parameters of artificial lighting to daylighting which is the most comfortable for human. The most promising systems in terms of tunability of the CCT and other parameters are 4-component systems, such as RGBW

(red/green/blue/white) and RGBA (red/green/blue/amber) systems [21-23] since they offer much more combinations of visual and non-visual parameters than 2- or 3-component systems [22, 24].

In this paper, we explore two RGBW systems and the space of visual and circadian parameters that they can ensure to determine optimal combination of LEDs contributions according to the field of system's implementation. The capabilities of these systems to ensure circadian effect are studied using the Rea et al. model [16]. For determination of the colour rendering the IES colour fidelity index Rf and gamut index Rg [25] are used since they are more accurate than colour rendering index (CRI) and therefore are recommended by CIE for scientific use [19].

II. RESEARCH CONDITIONS

Two RGBW lighting systems are considered. They have the same red, green and blue LEDs (R,G,B), but different white LEDs: the first one - RGBW_W system has warm white (W_W) LED with CCT_{WW}=2985K (CRI 82, Rf 83), and the second one - RGBW_N system has neutral white (W_N) LED with CCT_{WN}=4026K (CRI 81, Rf 81). The W_W and W_N LEDs were chosen for the study since the analysis of the influence of the white LED on the parameters of the resulting light of RGBW systems showed impractical use of the cool white LEDs [26]. The pick wavelengths of R, G and B LEDs are 625 nm, 525 nm and 461 nm respectively. Two normalized spectral power distributions of the W_W and W_N LEDs used in the systems are shown by the dashed lines in Fig.1 together with photopic luminous efficiency function V(λ) and two circadian spectral sensitivity functions c(λ) according to Gall et al. [15] and Rea et al. [16] models.

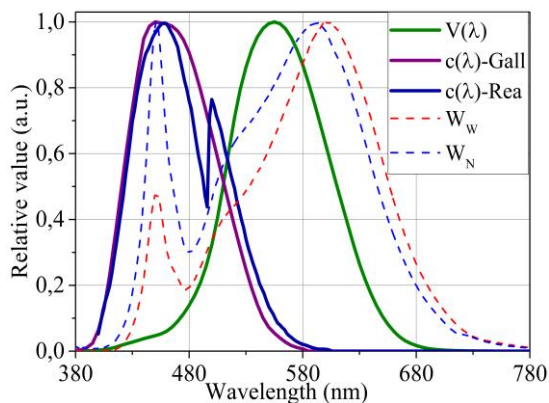


Fig. 1. The photopic luminous efficiency function $V(\lambda)$, the circadian spectral sensitivity $c(\lambda)$ according to Gall [15] and Rea [16] models, and spectral power distributions of the warm white (W_W) and neutral white (W_N) LEDs used in the clusters.

To explore the space of possible values of colour rendering and circadian parameters of the described systems, the SPDs of the resulting light are generated for different contribution of RGB-component. Due to the fact that illumination's similarity to natural lighting is associated with location of a colour (i.e. its chromaticity coordinates) on the Planckian locus on the CIE chromaticity diagram, in this work study is carried out along the Planckian locus within the CCT range 2500 –

6000K with 500K step and at 7000K. Each CCT is obtained for eight different RGB-contributions being equidistant geometrically on the CIE chromaticity diagram. Examples of the chromaticity coordinates of the resulting light and schematic coordinates of the used LEDs are shown in Fig. 2. The RGB-contribution changes by changing the position of the RGB point (i.e. chromaticity coordinates of the resulting light of three coloured LEDs) along the ray with initial point W_W (or W_N) passing through the resulting point on the Planckian locus. Since position of the points W_W, W_N and resulting white light for each CCT are fixed, it is only the RGB-contribution that regulates the spectrum of the resulting light and, therefore, its colour rendering and circadian parameters. It should be noted that as the distance between the RGB point and Planckian locus increases, RGB-contribution to the resulting light decreases. Thus, SPDs and parameters of the resulting light are calculated for different RGB-contributions in a wide CCT range. It allows evaluating the capabilities of RGBW systems to provide an optimal combination of visual and non-visual parameters.

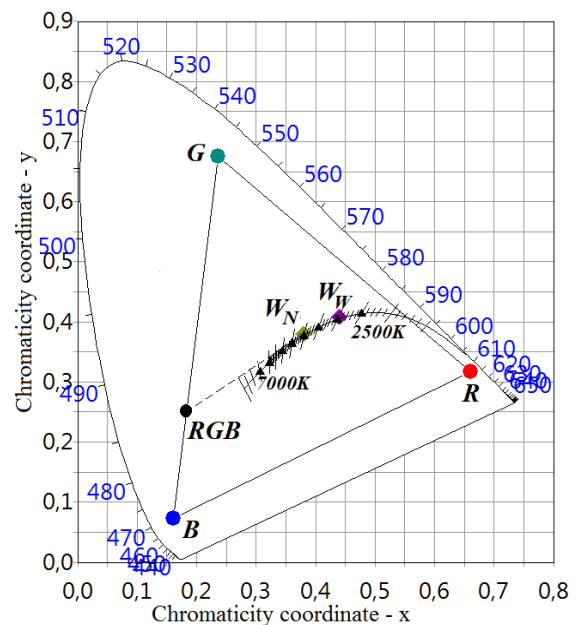


Fig. 2. CIE diagram with schematic chromaticity coordinates of red, green, blue, warm white and neutral white LEDs (R, G, B, W_W, W_N), and points of the resulting light on the Planckian locus.

III. RESULTS AND DISCUSSION

Visual and non-visual parameters of the resulting RGBW light are calculated in the CCT range of 2500 – 7000K. They include colour fidelity index Rf, gamut index Rg, colour rendering index (CRI), the circadian light CL_A, circadian action factor a_{CV} and circadian stimulus CS for different visual corneal illuminance. An analysis of the obtained colour rendering values shows that the CRI and Rf values have similar dependencies on the RGB-contribution and their maximum values are gotten at the same RGB-contribution. The CRI and Rf maximum values of two RGBW clusters at different CCTs are presented in Table 1. There are also the corresponding values of the gamut index, circadian action factor and circadian light at a corneal illuminance of 300 lx that herewith obtained. Thus, for the RGBW_W and RGBW_N systems the maximum

CRI values varies in the ranges 82 – 97 and 56 – 97, while maximum Rf values are 86 – 93 and 70 – 92, respectively. But as already mentioned, maximizing colour rendering is not a criterion for the quality of light in terms of its non-visual impact on human circadian rhythms.

To evaluate the effect of the RGBW clusters on the circadian system the circadian light CL_A is calculated at different RGB-contribution. Its values at 300 lx are chosen for the comparison since this corneal illuminance was proposed as the beginning of the “bright appearance” [27,28]. The CL_A values at 300 lx as a function of CCT for RGBW_W and RGBW_N systems and their comparison with a blackbody radiator are shown in Fig. 3. As is apparent, the relative effectiveness of the RGBW systems for stimulating the circadian system may vary for a given CCT at different LEDs contribution. As the RGB-contribution increases, the CL_A value increases. And the RGB-contribution has a greater effect on circadian light at low CCT. Thus, the ranges of possible CL_A values change within 1-6% at 4000 – 7000K and 16-20% at 2500 – 3000K and more than twice at 3500K. This is due to the different types of response from the blue–yellow channel which is expressed by the parameter opp: opp<0 for the ‘yellow’ response being governed by the ipRGC and opp>0 for the ‘blue’ response being governed by the ipRGC and S-cones. At the CCTs higher than 4000K it is always positive.

TABLE I. MAXIMUM VALUES OF COLOUR RENDERING INDEX (CRI_{max}) AND FIDELITY INDEX (Rf_{max}), AND CORRESPONDING GAMUT INDEX (RG), CIRCADIAN ACTION FACTOR (acv) AND CIRCADIAN LIGHT AT A CORNEAL ILLUMINANCE OF 300 LX (CL_A) IN THE CCT RANGE OF 2500 K – 7000 K FOR TWO CLUSTERS.

CCT,K	RGBW _W					RGBW _N				
	CRI_{max}	Rf_{max}	Rg	acv	CL_A	CRI_{max}	Rf_{max}	Rg	acv	CL_A
2500K	82	86	108	0.33	257	56	70	114	0.36	281
3000K	97	93	102	0.41	305	77	85	110	0.44	321
3500K	97	92	101	0.51	368	96	92	103	0.50	136
4000K	97	90	99	0.56	206	89	86	98	0.58	196
4500K	96	89	100	0.68	266	97	90	101	0.69	259
5000K	96	89	99	0.75	319	97	90	101	0.74	313
5500K	95	89	100	0.81	368	97	90	101	0.80	361
6000K	95	88	99	0.87	413	96	89	99	0.86	405
7000K	94	86	98	0.97	487	95	88	99	0.96	482

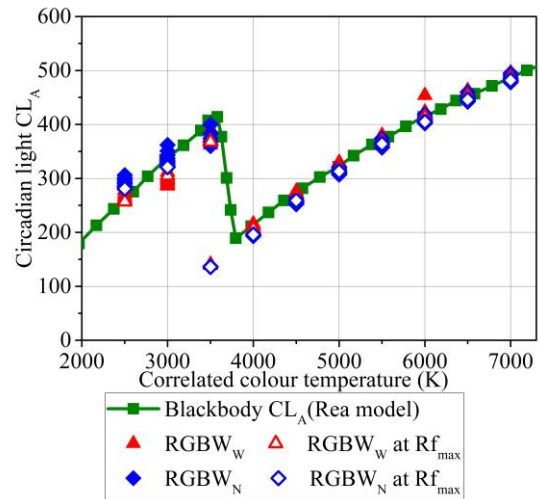


Fig. 3. The relative effectiveness of 300 lux corneal illuminance for a blackbody radiator for circadian system stimulation according to the Rea model [16], for RGBW_W and RGBW_N systems with different LEDs contributions at CCTs from 2500K to 7000K, and for these systems while the Rf values are maximal.

The limitation of light sources with fixed CCT (i.e. fixed SPD) is that their colour rendering and circadian action factor are also fixed due to their determination only by SPD. For a such white light sources of different origin (incandescent, fluorescent, LED lamps) with similar CCT values it was already shown the absence of the circadian dependence of the “dose of blue light” and almost a linear increase of it with the CCT increase [29]. This “dose” was proportional to the acv parameter and calculated using Gall model [15].

Conversely, in the RGBW systems it is possible to change SPD smoothly changing colour rendering and acv parameters. To explore in detail, the space of visual and circadian parameters that can ensure two considered clusters, it is obtained a series of achievable colour rendering and circadian action factors for each target CCT. The simulation results for fidelity index Rf versus acv (calculated using Rea model) in the CCT range 2500 – 7000K are presented in Fig. 4. The circadian action factors of the W_W and W_N LEDs without adding RGB-component are 0.38 and 0.56 respectively.

As expected, the calculated acv values increase with the increase of the CCT. Thus, its minimum value (0.33) is achieved at 2500K and maximum value (0.99) - at 7000K. According to Fig. 3, at some CCTs the circadian action factor has two boundary values that differ up to 5% while fidelity index Rf is the same. This increase opportunity of such systems, allowing to regulate the circadian effect without changing the colour rendering. A calculation of colour rendering index CRI for two considered RGBW systems showed similar dependence on acv but different numerical values (predominantly higher).

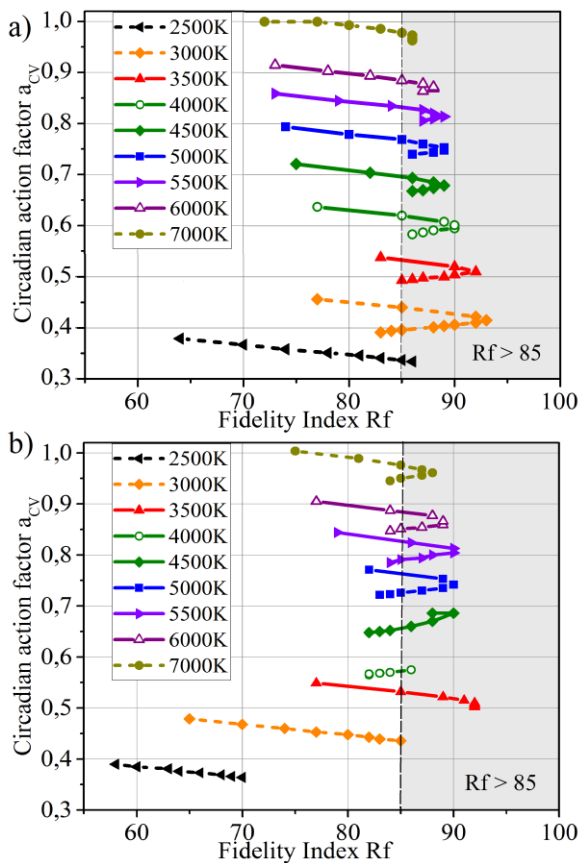


Fig. 4. IES fidelity index R_f versus circadian action factor (a_{cv}) for the CCTs from 2500 to 7000 K for RGBW systems with basic Warm (a) and Neutral (b) White LEDs.

The gray area in Fig. 4 indicates an acceptable criterion that the fidelity index R_f is above 85. Under this condition, the a_{cv} can reach values from 0.33 at 2500 K to 0.98 at 7000 K in the RGBW_W system and from 0.44 at 3000 K to 0.98 at 7000 K in the RGBW_N system. Any circadian action factor between these boundary values can be obtained by changing the CCT and (or) colour rendering.

Each SPD also allows to evaluate the corresponding percentage of melatonin suppression as a function of visual corneal illuminance ($E_{v,cor}$). This circadian stimulus CS is calculated for an hour exposure on the presumption that pupil has fixed diameter 2.3 mm [11,18]. It is ranges from 0 to 70%, where 5% is a working threshold, 35% and 70% are levels of half saturation and saturation of circadian activation, respectively [5]. Since in the RGBW system each CCT can be obtained by many different SPDs, it is possible to calculate achievable combinations of the CS and $E_{v,cor}$ for each CCT. Thus, one can choose an optimal combination of circadian stimulus and $E_{v,cor}$ for desired CCT by optimising SPD (i.e. regulating LEDs' contributions) and the light output.

A complete calculation of circadian stimulus for a wide CCT range allows to find out achievable area of the CS-versus- $E_{v,cor}$ space for considered system and thus, choose preferred combination of CCT, CS and $E_{v,cor}$ according to the lighting-design scenarios. Fig. 5 shows achievable area of the CS-versus- $E_{v,cor}$ space for RGBW_W system in compliance with the specified earlier condition that the fidelity index R_f is above 85. It is limited by

3500K and 7000K because the corresponding area for 2500–3000K are within the range indicated in Fig. 5. That is because of change in the type of response from the blue–yellow channel at 3500K and negative parameter opp (the ‘yellow’ response) for the low CCTs. Thus, the circadian effect increases with increase of CCT from 3500K to 7000K, but for 2500K and 3000K it is close to corresponding values for 4500K and 5000K, respectively. To induce 5% nocturnal melatonin suppression, it is needed one-hour light exposure of about 22 lx at 7000K or about 75 lx at 3500K. Similarly, to induce 35% of melatonin suppression it is needed one-hour light exposure of about 250 lx at 7000K or 700 lx at 3500K. So, if there is no significant difference in CCT choice for some applications, one can find the maximum possible level of corneal illuminance at the desired CS for comfortable lighting.

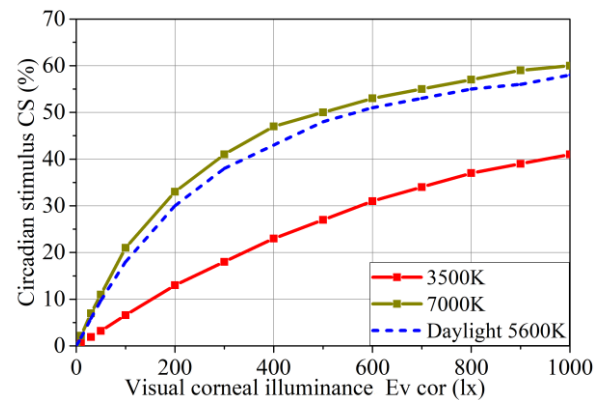


Fig. 5. Achievable area of circadian stimulus (CS) versus visual corneal illuminance ($E_{v,cor}$) for RGBW_W system at R_f above 85, and for measured daylight spectrum at 5600K.

Fig. 5 also contains for comparison a dependence for the spectrum of daylight at 5600K being measured at the solstice at cloudless weather conditions at the roof of the V. Lashkaryov Institute of Semiconductor Physic NASU (Kyiv, Ukraine (50°23'27.3"N, 30°31'48.6"E)). Since this dependence is within the achievable area it is possible to reproduce these values of circadian stimulus and corneal illuminance of daylighting by using RGBW system.

IV. CONCLUSIONS

In this work, we demonstrate the space of visual and non-visual parameters that can be achieved by RGBW systems. It is shown the range of possible values of circadian stimulus and circadian action factor that can be obtained while the fidelity index R_f is above 85. While often the choice of light sources is based on maximizing colour rendering and CCT tunability, this study of achievable area of the visual and circadian parameters enables to choose optimal combination of CCT, circadian stimulus and corneal illuminance for comfortable environment according to the lighting-design scenarios. For example, it is possible to change dynamically these parameters during a day to provide sufficient CS values during daytime, and low CS values (below 5%) in the evening so as not to disturb the natural circadian rhythms of human.

This study provides useful data for manufacturers of LED systems and lighting designers to create a comfortable lighting environment for work and leisure.

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Простір візуальних і циркадних параметрів RGBW-систем освітлення

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Анотація - Завдяки доведеному впливу світла на циркадні ритми людини, дослідники та розробники освітлювальних систем все більше уваги приділяють невізуальним параметрам світла та методах забезпечення безпечного комфортного освітлення. Це вимагає оптимізації спектрального складу випромінювання. Найбільш перспективними і функціональними, з цієї точки зору, є 4-компонентні системи освітлення RGBW (червоний-зелений-синій-білий) завдяки їх здатності динамічно змінювати спектральну характеристику і, відповідно, параметри результуючого світла. У цій роботі ми досліджуємо дві системи RGBW та простір візуальних та невізуальних параметрів, які вони можуть забезпечити. Серед візуальних параметрів визначаються кольоропередача та освітленість рогівки, а серед невізуальних параметрів – циркадне світло (CL_A), циркадний стимул (CS) та коефіцієнт циркадної ефективності (acv). Ці параметри розраховуються при різному внеску світлодіодів у результуюче світло у діапазоні корельованих колірних температур (CCT) від 2500 К до 7000 К. Додатково використовується прийнятний критерій, згідно якого індекс точності відтворення кольорів R_f вищий за 85. Показано, що за цієї умови можна отримати коефіцієнт циркадної ефективності в діапазоні 0,33-0,98 шляхом зміни CCT та (або) R_f. Також визначено досяжну зону простору циркадного стимулу та освітленості рогівки для систем RGBW. Це дозволяє обрати оптимальну комбінацію CCT, циркадного стимулу та освітленості рогівки для забезпечення бажаного рівня циркадного ефекту при комфортному візуальному сприйнятті залежно від часу доби та сфери застосування системи. Ці дані корисні для виробників освітлювальних систем та дизайнерів освітлення.

Ключові слова - змішування кольорів RGBW, регульоване біле світло, циркадний ефект, кольоропередача, точність відтворення кольорів.