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LED Lights With Hidden Intensity-Modulated Blue Channels Aiming for Enhanced Subconscious Visual Responses

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Abstract

A new form of light-emitting diode (LED) light suitable for general illumination is proposed to enhance subconscious, nonimage-forming visual responses, which are essential to our well-being. Pulsing light has been shown to reduce photoreceptor adaptation and elicit stronger subconscious visual responses at an indoor illumination level. Using the silent substitution technique, a melanopsin-selective flicker can be added into white light. A linear optimization algorithm was developed to suppress any perceivable fluctuation of light intensity and colors of illuminated objects. Two examples of lights are given to illustrate the potential applications of the proposed multi-LED light for general illumination and therapeutic purposes.

Index Terms

Light emitting diodes (LEDs); solid-state lighting

1. Introduction

Solid-state lighting based on light-emitting diodes (LEDs), as well as organic LEDs, has been rapidly adopted as the next-generation lighting technology [1]. LEDs not only are energy efficient but their capabilities to create light outputs with tailored spectra and intensities have enabled endless possibilities unavailable from incandescent and fluorescent lighting technologies. Recently “full-spectrum” or “day-light simulating” LED luminaires have gained much attention in the LED industry, aiming to deliver high-quality light to improve our well-being, given that an average person spends a good amount of time indoor [2]. Although the actual health benefits of these new forms of lights are still unclear [3], [4], it has been shown that the typical illuminance (~200–500 lux) for indoor lighting, which is

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generally 20 to 100-fold lower than natural daylight, is insufficient to properly stimulate subconscious physiological responses [5]–[8], such as suppression of nocturnal melatonin release [9] and entrainment of circadian rhythms [10]. These physiological responses are mediated by intrinsically photosensitive retinal ganglion cells (ipRGCs) which contain the blue-sensitive (λ_{max} 480 nm) photopigment melanopsin. Inadequate daylight exposure has been linked to poor sleep quality, seasonal affective disorder (SAD) [11] and depression [11]–[13]. The critical question is how to trigger subconscious visual responses at the indoor lighting level. Recent scientific discoveries have suggested a solution, that is to use a pulsed blue light [14]–[21]. An intermittently varying blue light intensity reduces melanopsin adaptation and enhances the responses of ipRGCs. Importantly, a pulsed light has been shown to lower the intensity needed to trigger robust ipRGC responses by as much as two orders of magnitude [16]–[18]. It is, therefore, expected that incorporating temporally modulated blue light into a white light source can effectively boost subconscious responses at a typical indoor illuminance level. However, the lack of precedence or know-how in using intensity-modulated lights for general illumination has prevented researchers from conducting a systematic study using these lights in various realistic lighting environments (e.g. offices, schools and hospitals). Such a study can have far-reaching impacts on the next-generation lighting technology. The goal of this paper is to develop and present a feasible implementation scheme using multi-color LED devices to “hide” the blue light pulses from observers and achieve a light output quality suitable for general illumination. Our results can be readily implemented in an LED luminaire which will offer vision researchers the necessary tool to conduct further research examining the impact of lighting on our well-being.

2. Methodology

The key to adapting a pulsed blue light for general illumination is to compensate for the periodic intensity change while at the same time mix other colors such as green and red to generate a stable white light output with a suitable color quality for general illumination. The compensation scheme needs to achieve stability for both the light source and scenery variations of the illuminated environment. The idea is illustrated in Fig. 1 by introducing two blue channels, one at a wavelength at which melanopsin is most sensitive (i.e. at or near 480 nm) and the other at a wavelength triggering a weaker melanopsin response (i.e. farther from 480 nm). The two blue channels will be turned on alternately. To generate a white-light output, a green and a red channel will also be added. The intensities of the green and red channels will need to be temporally modulated to compensate for the differences of the two blue channels, that is, the spectrum of the white light output is oscillated between two spectral states, one maximally and one minimally stimulating melanopsin. The optimal frequency of melanopsin modulation is around 0.07 Hz according to a previous study on rodent ipRGCs [18] and their apparent similarity to primate ipRGCs in melanopsin-based light responses [22]. For convenience, we will refer to the two spectral states as “melanopsin-max” and “melanopsin-min” spectra in the following discussions.

The selection of the wavelengths for the four (or more) LED channels, consisting of at least two blue, one green, and one red, are based on the silent substitution technique [23]–[31]. Since color perception is primarily mediated by cone photoreceptors, two stimuli with

dissimilar spectral power distributions can look identical to an observer if both spectra produce equivalent responses among the three cone channels. Such spectra are called cone metamers and the process of substituting one metamer with another is called silent substitution. In our lights, the melanopsin-max and melanopsin-min spectra need to be cone metamers.

After the wavelengths of the color channels are selected, the temporal modulation scheme is determined by minimizing the environmental flickering. Although the melanopsin-max and melanopsin-min spectra are cone metamers, the reflections from illuminated objects are generally not. To minimize the visible change, we first constrain the maximum change of stimulation by the reflected light to the three cones and then calculate the color inconstancy index (CII) [32]. We repeat this process for reflections off the first eight CIE Munsell test color samples (TCS) [33] and adjust the intensities of different color channels until the maximum change of the cone responses is less than the set limit. We then calculate the CII for each TCS. The CII value provides a quantitative measurement on the perceived color change in by two different illuminants. A CII of 1 describes a barely perceptible color difference in side-by-side sample comparisons by an average viewer, while larger values reflect greater, more readily perceived color differences. Color inconstancy is typically calculated to gauge the degree of color fidelity of a color sample with a change of illuminants, but in our case, we apply this methodology to predict the inconstancy of the scene illuminated by the same light source with an oscillating spectral output. It is worthwhile to note that we have chosen to limit the allowable change in cone responses instead of CII as our constraint. This is because the equation to calculate CII is nonlinear and hence prevents us from applying a simpler linear programming method, but as a larger change in cone responses is expected to lead to a higher CII, the choice of constraining the cone response change is still appropriate.

We define the change of the cone responses as a Weber contrast by integrating the melanopsin-max spectrum with the cone responses and taking the difference from the value for the melanopsin-min spectrum. To calculate the CII, we use the CIE color difference equation (2000), CIEDE2000. We first apply a chromatic adaptation transform for both the melanopsin-max and melanopsin-min spectra with respect to the reference illuminant best suited for use with CIEDE2000 [34]. Since this difference equation operates on the basis of CIELAB, the reference illuminant is D65 with an illuminance level of 1000 lux. The adaptation transform is necessary for the index to correlate with visual evaluation. The selected transform is CAT02 with sharpened cone fundamentals; it is the most recent recommendation from CIE and can be found in the CIECAM02 specifications. Since the responses of cones to the illuminant are fixed, the degree of chromatic adaptation is assumed to be complete and set to 1. This assumption is valid because the color coordinates of the illuminant do not shift and there is no heterogeneous mixing of scene lighting with another source. The TCS spectral reflectances are integrated with the spectral profile of first the melanopsin-max and then the melanopsin-min and tristimulus values calculated. The transform is applied to calculate corresponding color coordinates for TCS reflectances under the reference illuminant. Once the corresponding color coordinates under the reference illuminant are specified for a TCS for the two spectra, a CII is calculated.

The algorithm of our design process is as follows. We vary the number of LEDs, the color temperature of the light, the LED linewidths, and the maximum allowable change (referred to as the tolerance in the following) in cone responses. We adopt an “elimination approach” by iterating the correlated color temperature (CCT) from 3000 to 11000 K in 100 K intervals. For each CCT value, we obtain the melanopsin-min spectrum such that it is on one of its isotemperature lines along the Planckian locus and the melanopsin-max spectrum using the silent substitution. We then check whether these two spectra induce a change in cone responses from all TCS’s within the set limit of “tolerance”. If they do, we proceed to calculate the CII and other light quality indices including color-rendering index (CRI) [33] and color quality scale (CQS) [35]. We also determine the melanopsin contrast which is defined as the Michelson contrast between the melanopsin-max and the melanopsin-max spectra.

Results and Discussions

To discuss the results, we choose two examples with different tolerances, one set at 5% and the other at 50% to illustrate the dependence of the light quality (measured by CII, CRI, and CQS) and melanopsin contrast on the input parameters such as number of LEDs and LED linewidths. Fig. 2 and Table 1 show the results of two illuminants containing four LEDs, labeled as “Illuminant 1” and “Illuminant 2,” respectively. Each illuminant is temporally modulated between two spectra shown in Fig. 2(a) and 2(d). The two spectra are cone metamers, and hence, the color coordinates will remain constant during the modulation.

The “Illuminant 1” (see Fig. 2 (a)) has a small (5%) tolerance in cone response shift (see Fig. 2(c)), which leads to a low CII (mean is 1.6) as shown in Fig. 2(b). In combination with a large linewidth (50 nm), this light source produces a 4.7% melanopsin contrast which has been shown to be sufficient to significantly modulate the pupil diameter [36], a physiological response linked to ipRGC stimulations. With the low CII and high CRI of around 80, the “Illuminant 1” is expected to be suitable for general illumination.

The “Illuminant 2” (see Fig. 2(d)) has a larger (50%) tolerance in cone response (see Fig. 2(f)), which leads to a larger melanopsin contrast of 30.1%. The CRI (CQS) values of its minimum and maximum spectra are lower at 65 (37) and 80 (68). The mean CII for 14 TCSs is 8.2 (see Fig. 2(e)), and the CII for TCS 12 is 26.7, which is more than twice the second largest value of 12.0, for TCS 10. The environment illuminated by “Illuminant 2” is expected to exhibit noticeable temporal fluctuations, albeit at only 0.07 Hz, which was found to be optimal to trigger melanopsin-based responses. As a result, this illuminant may not be suitable for general illumination. But with a high melanopsin contrast, it is likely to trigger a significantly greater ipRGC response than the illuminant with 5% tolerance (see Fig. 2(a)) and, hence, may be useful as a therapeutic light for treating SAD or other conditions arising from poor ipRGC stimulation. These subtle shifts can probably be reduced by using a light source that alternates between the maximum and minimum spectra in a smooth, sinusoidal fashion. Existing light therapies using bright blue or very high color-temperature white lights has been found to improve sleep quality, reaction times, alertness, and ameliorate SAD symptoms [19], [38]–[40] but require prolonged dedicated viewing. The “Illuminant 2” can

potentially circumvent such inconvenience, by allowing users to receive therapy while engaging in normal daily activities.

To simulate any failure in metamerism due to observer variability, CII was also calculated for the “Illuminant 1” using a modification of the color matching functions with change of observer functions, the deviation functions of the optimized deviate observer [37]. Shifts in CII with change of observer are relatively small (indicated by the black lines in the bars in Fig. 2(b)) and hence the effect of observer variability is likely negligible for general illumination applications.

Figs. 3 and 4 show the trend for different input conditions including different numbers of LEDs and color temperatures (represented by different color coordinates (*x, y*)). The linewidth and tolerance are fixed at 10 nm and 5%, respectively. Generally, more LEDs produce a higher melanopsin contrast (see Fig. 3) but are accompanied by poorer CII (see Fig. 4). With more LEDs comes more instability in color appearance as a high proportion of simulation states cause an increase in CII as well as larger changes in CRI and CQS. One remedy to counteract this instability is to decrease the independence of the LED channels by broadening the spectral width of each LED. Setting a narrow cone-change tolerance range with respect to our environmental constraints, for instance ±5%, results in permitted contrast solutions that remain smaller than those that are solely limited by the effects of spectral broadening – up to FWHM values as high as 50 nm. The benefit of large spectral width was demonstrated by the “Illuminant 1.”

Table 2 summarizes the general relationship between the input parameters and the characteristics of light. We use a linear fit model and a survey of R^2 values provided by this model for analysis. Contributions of our inputs–number of independent LED channels, LED linewidths, color temperature and tolerance–to our outputs–either melanopsin contrast, CII, or CRI value–is assessed by removing each input individually from our linear fit model (first eight TCS simulations) and recording the R^2 values. R^2, with a value ranging from 0 and 1, describes the degree to which our model inputs account for the behavior of the specified output. In our analysis, except for the tolerance for which a logarithmic scale is chosen, linear scales are chosen for all other inputs. By comparing the R^2 values between the case where “all inputs” are considered and the case where one input is removed, the degree of significance of the input that is removed can be assessed. In Table 2, it can be seen that the number of independent LED channels contributes surprisingly little to the contrast calculations. Instead, the tolerance has the largest impact on the contrast, which is also evident from Fig. 4(f). The LED linewidth has a sizeable, but less significant, impact on the contrast values. The color temperature appears to have little effect on contrast optimization. R^2 analysis with CII and CRI set as outputs reveal similar contributions from our inputs. There is one exception: tolerance has almost no effect on “CRI min” because the melanopsin-min spectrum is chosen based on the desired CCT.

In addition to theoretical analysis, a preliminary prototype comprising of five LED channels (with a total of 20 LED devices) at wavelengths of 456, 488, 540, 592, and 632 nm, respectively, was fabricated based on the algorithm described above. Under temporal modulation, the light appeared to be quite stable in color and did not cause any discomfort or

ocular fatigue over several hours of observation. However, a more systematic large-scale human study is necessary to investigate the potential side effect of repeated pupil dilations and constrictions caused by melanopsin modulation.

Another potential drawback of the proposed LED light is that the melanopsin-directed oscillation is not completely subconscious, as human subjects have been reported to be able to discriminate melanopsin-selective metamers [41]. However, subsequent work found that melanopsin-selective metamers may affect penumbral cones [42], and therefore, the contribution of melanopsin stimulation to brightness perception remains unclear, but even if the melanopsin-selective oscillation in our light source can be consciously detected, its low frequency and sinusoidal waveform should help make the perceptible brightness fluctuation less disruptive.

Conclusion

Intensity-modulated blue light has previously been shown to lower the light intensity needed to trigger ipRGC and subconscious visual responses by suppressing the adaptation of ipRGCs to the input light. Yet, it has been unclear when incorporating dynamic modulation into a general illuminant is possible. In this paper, we have proposed an approach based on silent substitution to hide the periodic intensity change of the blue component in a white light source. The complexity of incorporating silent substitution arises from the multiple environmental variables we seek to control which consist of subtractive objects, each with its unique reflectance properties. We have developed an algorithm to minimize the environmental flickering and studied the relationships between melanopsin contrast, color fidelity and/or quality, and constancy of scene appearance. Using four or more independently controlled LED channels, an illuminant with a good color rendering index and color temperature suitable for general illumination has been suggested.

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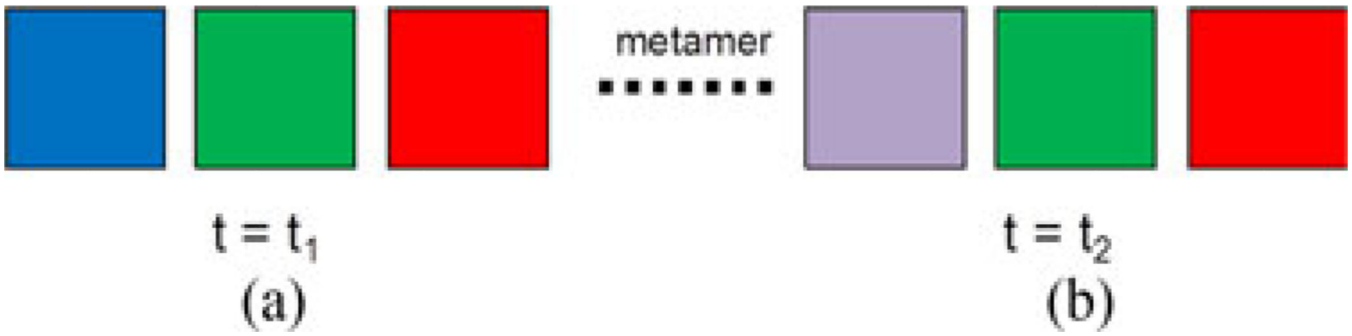

Fig. 1.

Proposed scheme to incorporate a pulsed blue light in a white light source for general illumination. Light consisting of four color channels, two of which are blue, one green, and one red, is illustrated. The two blue channels are chosen such that one blue channel will strongly stimulate melanopsin, and the other will stimulate melanopsin relatively weakly. The two spectra, i.e. “melanopsin-max,” as shown in (a), and “melanopsin-min,” as shown in (b), are alternated in time. They are also designed to be metamers so that the intensity modulation of the melanopsin-stimulating blue light can be hidden from rod/cone-based visual perception.

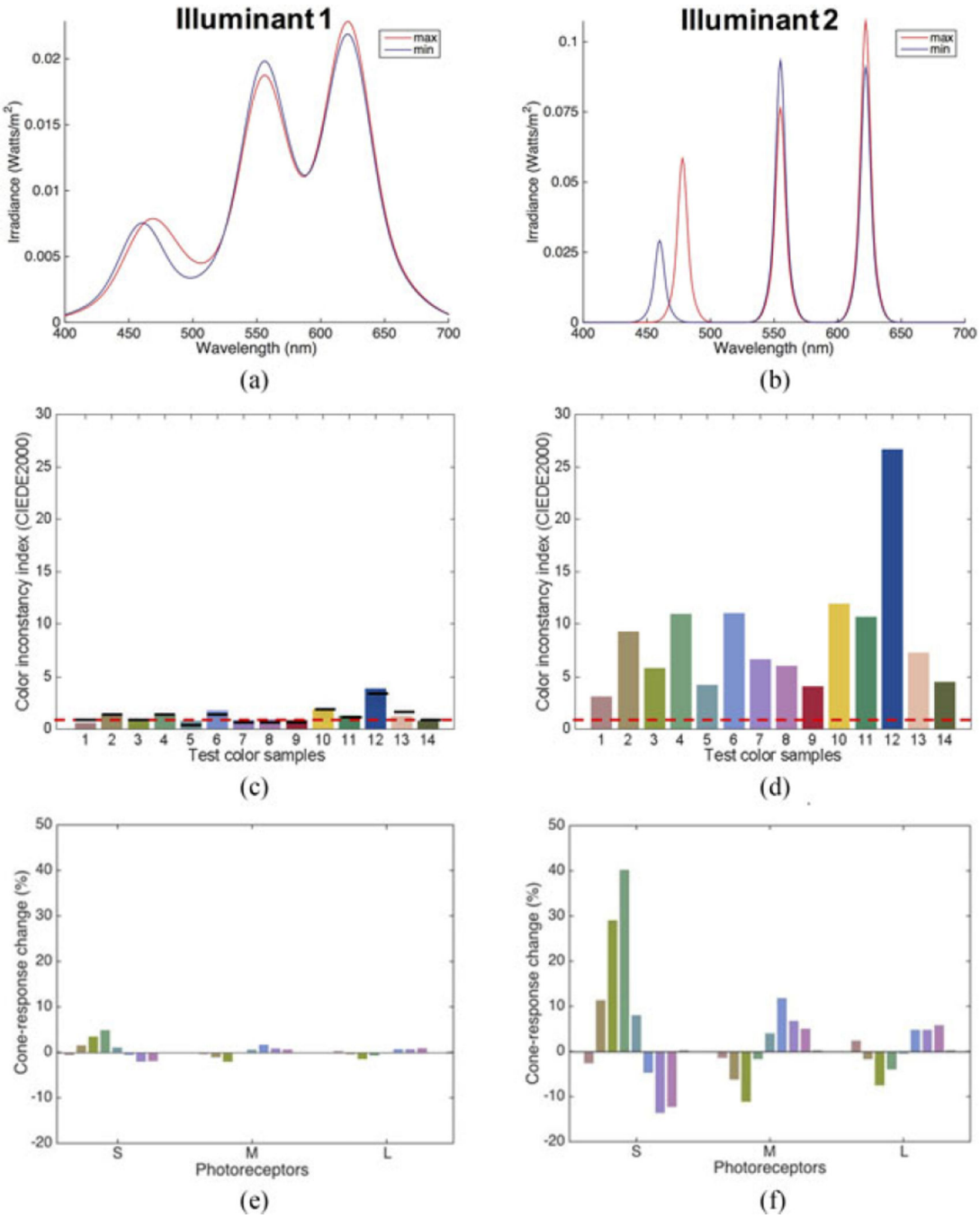

Fig. 2.

Spectra and metrics for two example illuminants incorporating a pulsed blue light component. (a), (d) Spectra of the two illuminants. (a) has a 5% limit in cone response change, and (d) has a 50% limit in cone response change. (b), (e) Individual CII values for 14 TCSs specified in CRI calculations for the two illuminants. (b) corresponds to (a), and (e) corresponds to (d). (c), (f) Amount of cone response change to the first eight TCSs, as spectra oscillate between the melanopsin-max and melanopsin-min states for the two illuminants. (c) corresponds to (a), and (f) corresponds to (d).

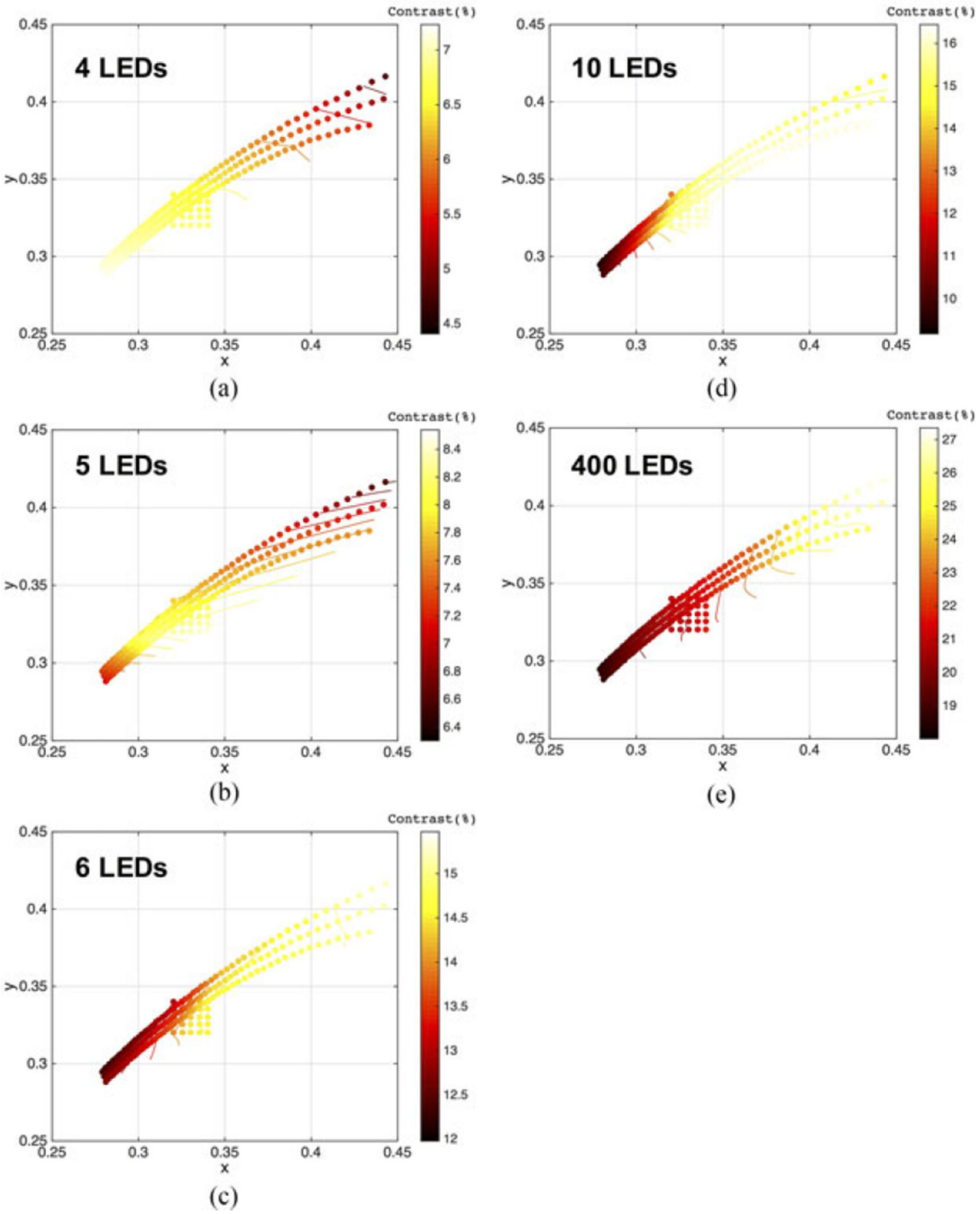

Fig. 3.

(a)–(e) Melanopsin contrasts for simulations with 4, 5, 6, 10, and 400 LED channels, respectively, plotted on the CIE chromaticity diagram using 10° color matching functions. The correlated color temperature of maximum contrast shifts when the number of independent LED channels is adjusted. In (a)–(e), solid curves indicate isocontrast contour demarcations.

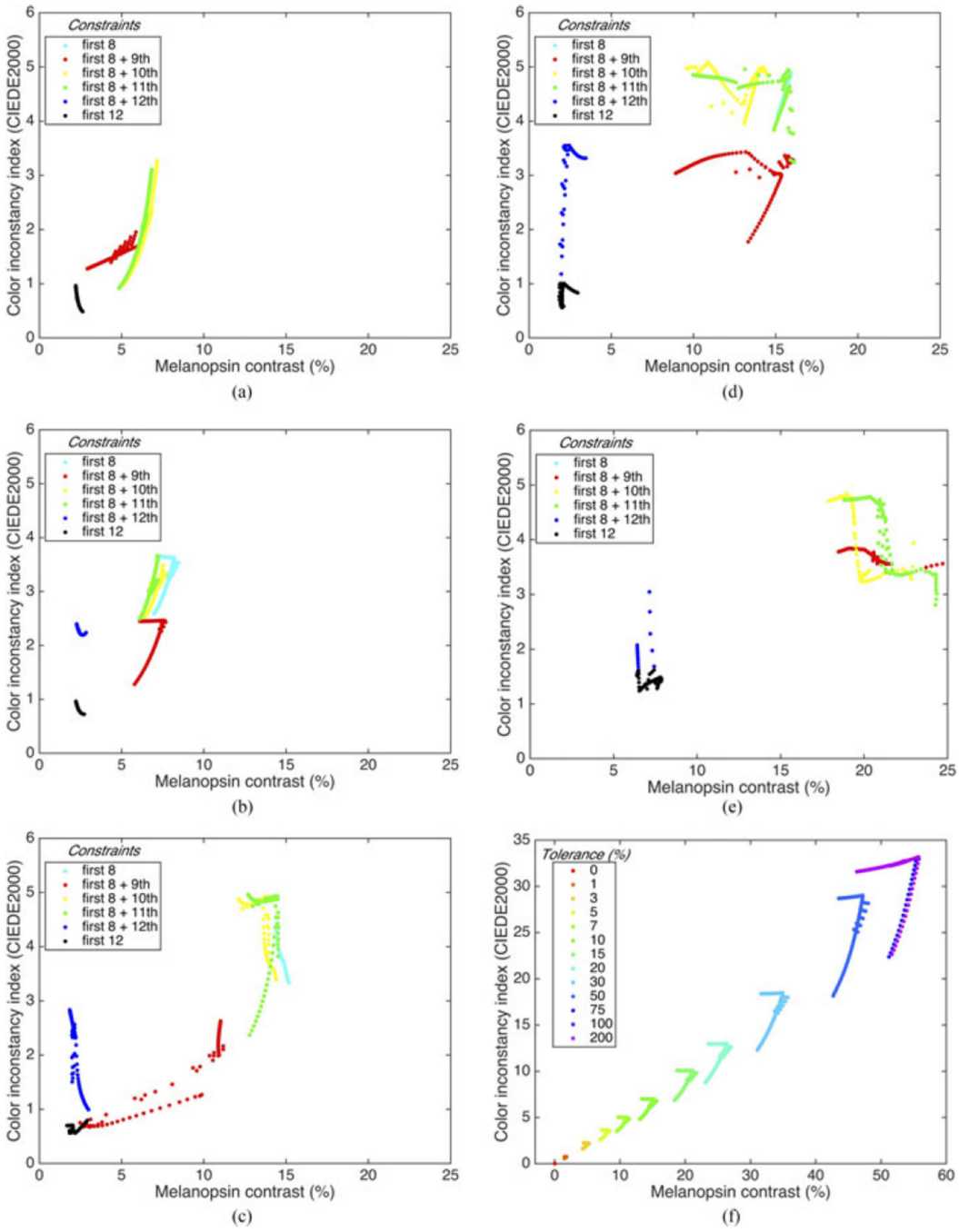

Fig. 4.

(a)–(e) Mean CII vs. melanopsin contrast as TCS boundary conditions are expanded for lights with 4–400 independent LED channels. TCS 9-12 are high chroma red, yellow, green, and blue colors respectively, which are excluded from the calculation of general CRIs. “first 8” refers to the inclusion of the first eight TCSs in the constraint matrix “first 8 9th” means including the first eight TCSs plus the ninth TCS, etc. The panels reveal trends toward reduced CII and contrast as additional TCSs are included in the constraints. Including TCS 12 (strong blue) in the boundary conditions shows the largest drop in melanopsin contrast,

often with little benefit to reduction in mean CII. (f) Correlation between the averaged CII values from TCS 1-8 and the melanopsin contrast shows a consistent trend with the tolerance.

TABLE 1

Values of Key Lighting Parameters for the Two Illuminants Shown in Fig 2

Parameter	Illuminant 1	Illuminant 2
(x_{10}, y_{10})	(0.437, 0.404)	(0.437, 0.404)
CCT (K)	3240	3300
Melanopsin Contrast (%)	4.7	30.1
Mean CII	1.22	8.18
CRI max	85	80
CRI min	79	65
CQS max	72	68
CQS min	64	37

(x10, y10): the color coordinates in the CIE 1964 color space. “CCT”: the correlated color temperature of the illuminant. “Contrast”, the Michelson contrast of the melanopsin response induced by the maximum- vs. the minimum-melanopsin spectrum. “Mean CII,” the average color inconstancy index with respect to all 14 TCSs. “CRI min,” “CRI max,” “CQS min,” and “CQS max” are the color rendering index and color quality scale values corresponding to the melanopsin-max and melanopsin-min states of the illuminants.

TABLE 2

R^2 Values From Linear Fits Between Each Output and the Inputs

Output: / Input	Contrast	CII	CRI max	CRI min
All inputs	0.843	0.812	0.67	0.645
All inputs – LEDs	0.806	0.783	0.574	0.608
All inputs – CCT	0.839	0.804	0.665	0.616
All inputs – Linewidths	0.576	0.543	0.385	0.391
All inputs – Tolerance	0.268	0.214	0.670	0.243

In row 1, all inputs were included in the analysis; in rows 2–5, one input was removed for the analysis. CRI min and CRI max represent the CRI values obtained for the melanopsin-min and melanopsin-max spectra, respectively.