Lighting Res. Technol. 2020; **52**: 167–188

The effectiveness of light-emitting diode lighting for providing circadian stimulus in office spaces while minimizing energy use

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Received 8 January 2019; Revised 5 February 2019; Accepted 8 February 2019

Architectural lighting has traditionally addressed visual performance and horizontal illuminance on the work plane, later focussing on energy efficiency, while only recently paying particular regard to human health outcomes. The present study evaluated the effectiveness of several light-emitting diode lighting strategies for delivering circadian stimulus to occupants of a typical office space while minimizing energy use. The study employed photometric simulations in a typical open-office space, delivering a criterion circadian stimulus of 0.3 to calculation points modelled at the simulated occupants' eye level. Six luminaire types, two luminous intensity distributions, six spectral power distributions and two horizontal illuminances were evaluated, resulting in 144 unique lighting conditions. Additionally, the study calculated the discomfort glare for selected luminaires with the highest total lumen output, smallest aperture and direct-only luminous intensity distributions at the higher of the two horizontal illuminances (500 lx). The most impactful strategy involved supplementing common overhead lighting with a desktop luminaire delivering light directly to the simulated office occupants' eyes, which provided greater circadian stimulus and used less energy than overhead luminaires that were capable of delivering the criterion circadian stimulus of 0.3.

1. Background

Traditionally, architectural lighting has been engineered, specified and designed primarily to address visual performance and horizontal illuminance (E_H) on the work plane. In the 1940s and 1950s, however, lighting engineers and designers began to consider issues beyond visual performance, such as the apparent brightness of a space,[1,2] and explored ways to mitigate the undesirable 'cave effect' of lighting techniques that delivered illuminance to the work plane with as little 'wasted' light as possible. A consequent, new-found importance of illuminating vertical surfaces and ceilings to enhance the perception of brightness[3,4] spurred manufacturers to develop luminaires with luminous intensity distributions that directed luminous flux in directions other than straight down. Following suit, designers began to consider indirect illumination as a means for satisfying the visual and psychological goals of lighting the interior environment.

Recently, architectural lighting's scope has broadened to consider light's non-visual characteristics, specifically as they affect the human circadian system. Light is the primary exogenous cue for regulating the body's

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 10.1177/1477153519834604

endogenous circadian rhythms, synchronizing (or entraining) them with the 24-hour light–dark cycle at one's local position on Earth. The characteristics of light stimuli are also central to this process, specifically in respect to the amount (or level) of light received at the cornea, its spectral properties, the timing of the light exposure and the duration of that exposure.[5–7] More importantly, light also must reach the retina to induce a response and, therefore, vertical illuminance (E_V) is crucial for circadian phototransduction, which is the process that transforms light incident on the retina into electrical signals for the master biological clock, the suprachiasmatic nuclei (SCN) in the brain's hypothalamic region. The timing signals distributed throughout the body by the SCN help to regulate circadian rhythms such as the sleep-wake cycle, core body temperature and various metabolic processes such as the secretion of hormones (notably, melatonin and cortisol), essentially telling the body to do the right things at the right time.

In addition to stimulating the circadian system, light also exerts an acute alerting effect on humans that is similar to that provided by a cup of coffee. Recent research suggests that the characteristics of a given light stimulus, principally its amount and spectral properties, affect alertness and the timing of the SCN differently.[8] Although short wavelength 'blue' light can elicit alertness, for example, filtering out blue light or providing exposure to long wavelength 'red' light can either maintain or increase alertness compared to non-filtered light or dim light. However, unlike exposure to blue light, which can acutely affect the body's production of the hormone melatonin (a well-established circadian system marker), red light can deliver a similar alerting effect without suppressing melatonin and disrupting circadian rhythms.[9] Research has shown that disruption of circadian rhythms is associated with increased risk for negative health outcomes such as metabolic and cardiovascular disease,[10] some forms of cancer,[11] sleep disruption[12] and various problems relating to mood and general health.[13] A recent field study of circadian-effective light exposures among government office workers, for example, demonstrated that high levels of circadian-effective light received at the eye, both in the morning and throughout the day, improved measures of night-time sleep, daytime alertness and overall mood.[14,15]

Presently, there is no widely agreed upon metric for characterizing circadian light and quantifying light's effect on the human circadian system. Among the recently proposed metrics is 'melanopic illuminance',[16] or flux density weighted by a luminous efficiency function based on the action spectrum of melanopsin, which is the photopigment in the retina's intrinsically photosensitive retinal ganglion cells (ipRGCs). The ipRGCs' axons form the retinohypothalamic tract that links the retina to the circadian system's master clock. Although this metric has been adopted as 'equivalent melanopic lux' (EML) in the architectural lighting standards developed by the International WELL Building Institute,[17] it has not been sanctioned by any independent standards organization and is inconsistent with scientific evidence showing that all three classes of photoreceptors (i.e. rods, cones and ipRGCs) participate in human circadian phototransduction.[18,19]

Field and laboratory studies conducted by the Lighting Research Center (LRC) have tested and verified the circadian stimulus (CS) metric, which quantifies light's effectiveness for stimulating the circadian system as measured by acute suppression of melatonin after a 1-hour nocturnal light exposure from threshold ($CS \approx 0.1$) to saturation ($CS \approx 0.7$).[7,20–22] It should be noted that, although consistent with neuroanatomy and neurophysiology of the circadian system and with current scientific literature, the CS metric also has not been sanctioned by any independent standards organization, although it has been validated in many field studies.[14,15,23–26] While it has been shown that delivering a CS of at least 0.3 for a minimum of 2 hours during the daytime is beneficial for circadian entrainment[14,23,24] and for increasing alertness and energy levels,[15,25,26] an undesirable consequence is that more energy can be required to deliver the appropriate, typically higher, amount of light to the eye than is required for visual performance on the work plane. Interior lighting that is beneficial for promoting entrainment and alertness therefore has a strong potential to increase energy use compared to systems designed for visual performance, thereby countering lighting industry trends for energy conservation that have been in place over the past several decades.

The present study's primary aim was to evaluate the effectiveness of several light-emitting diode (LED) lighting strategies for delivering CS to occupants of a typical office space while minimizing, or even preventing, increased energy use. The study employed photometric simulations of these strategies in a typical open-office space, delivering a criterion CS of 0.3 to calculation points modelled at the simulated occupants' eye level. To account for real-world factors that can hinder or block the delivery of CS to occupants' eyes in office spaces (e.g. shading from furniture and/or the contours of the human face), the study also evaluated the lighting strategies for delivering a design criterion CS of 0.4.

Since CS is dependent on the level of E_V received at the eye, the authors hypothesized that luminaire types delivering higher E_V/E_H ratios would provide a higher CS to lighting power density (CS/LPD) ratio. We also hypothesized that as the amount of short-wavelength light delivered by the light source increased, higher levels of CS for equal energy use would be obtained. However, it was also expected that increasing the amount of light at the eye would yield a greater increase in CS exposures than those produced by changing the light sources' spectra. Lastly, the authors hypothesized that a scheduled CS dosage strategy delivering high CS in the morning to promote circadian entrainment and a reduced dose for the remainder of the day could potentially limit energy use.

2. Method

2.1. Photometric simulation model

A typical open office space, measuring 16.8 m × 14.6 m (55 ft × 48 ft) with a 2.7 m (9 ft) high ceiling, was modelled using photometric calculation software (AGi32 version 18, Lighting Analysts, Littleton, CO, USA). The room model was assigned typical surface reflectances of 20%, 50% and 80% for the floor, walls and ceiling, respectively. Each of the room's model workstations consisted of a cluster of four desks, with a total of four workstations (16 desks) in the entire room model. Each desk was surrounded (75%) by partitions whose heights were set at 1.5 m and whose components were assigned reflectance values of 50%. The photometric calculations were obtained using a 15 cm × 15 cm grid of E_H points arrayed on work surfaces at 75 cm above finished floor (AFF) and E_V points arrayed at 15 cm intervals along a line 1.2 m AFF in the orientation of the viewing angle modelled for the occupants (Figure 1). The E_V points used for the CS measurements were averaged for eight modelled occupants seated in different locations throughout the room. The layouts for all luminaires were optimized to provide the study's criterion E_H levels and, where necessary, the luminaires' lumen packages were adjusted to provide the target E_H levels in the room model using a minimum number of luminaires (Figure 2).

The photometric simulation examined how CS exposures might be maximized while limiting energy use by varying the luminaires'

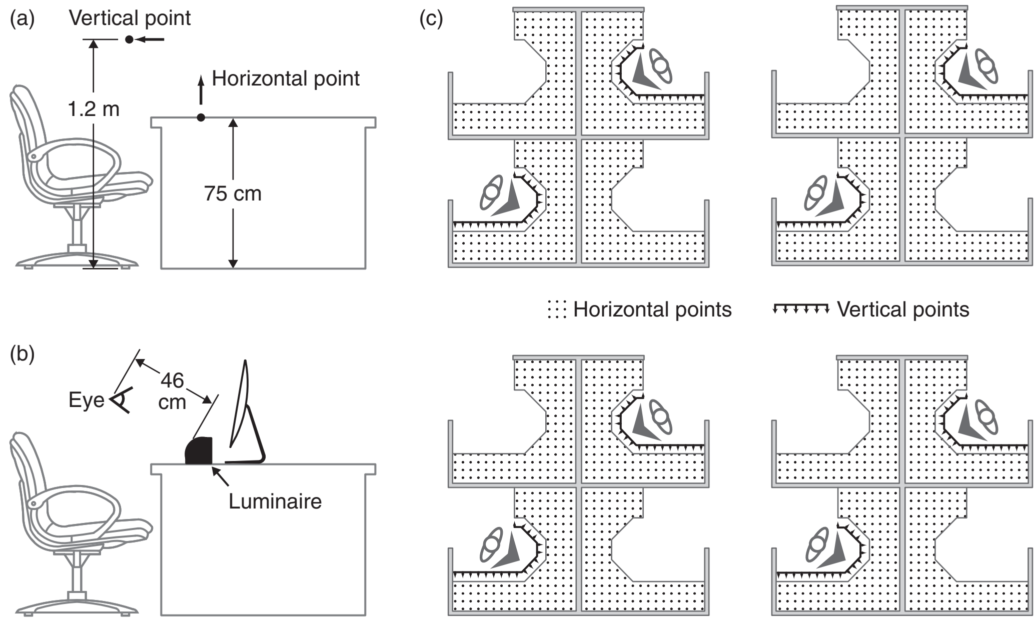


Figure 1 The orientations of data collection points used for the photometric simulation, showing: (a) E_H and E_V points at individual workstations, (b) E_V points in respect to the desktop luminaire and (c) E_H and E_V points distributed throughout the office model in respect to the eight modelled office occupants

luminous intensity distribution and spectral power distribution (SPD), supplementing existing overhead luminaires with a desktop luminaire, and providing a scheduled CS dosage that varied throughout the day. The lighting conditions were evaluated for their calculated CS/LPD ratio as a performance metric (expressed as a decimal percentage), where LPD is defined as the total electric lighting watts per square foot (W/ft^2) of space over the entire simulated office (see Figure 2). (LPD is a measure of lighting power density commonly found in building energy codes and therefore should be familiar to lighting engineers, specifiers and designers.) The higher the CS/LPD ratio, the more energy-effective the lighting strategy. Since the variable CS schedule involved the element of time, watt-hours per square foot per day (Wh/ft^2/day) served as the performance metric in that aspect of the analysis. (Conversions to Système International (SI) compliant units are provided in parentheses for the convenience of the reader.)

2.2. Modelled lighting apparatus

The simulation modelled six ceiling-mounted luminaire types: (1) 2×2 troffer (measuring $0.6\,m \times 0.6\,m$), (2) 2×4 troffer (measuring $0.6\,m \times 1.2\,m$), (3) direct linear pendant, (4) direct/indirect linear pendant, (5) indirect linear pendant and (6) recessed downlight. Calculations performed to evaluate any potentially problematic shadowing in the simulated office, particularly considering the modelled 2.7 m ceiling height, indicated that illuminance uniformity on the workplane for the direct/indirect pendant configuration was 2.5:1 (avg:min) and 4:1 (max:min). It should be noted that the former value was slightly higher than the Illuminating Engineering Society of North America (IES) recommended ratio of 1.5:1 (avg:min).[27]

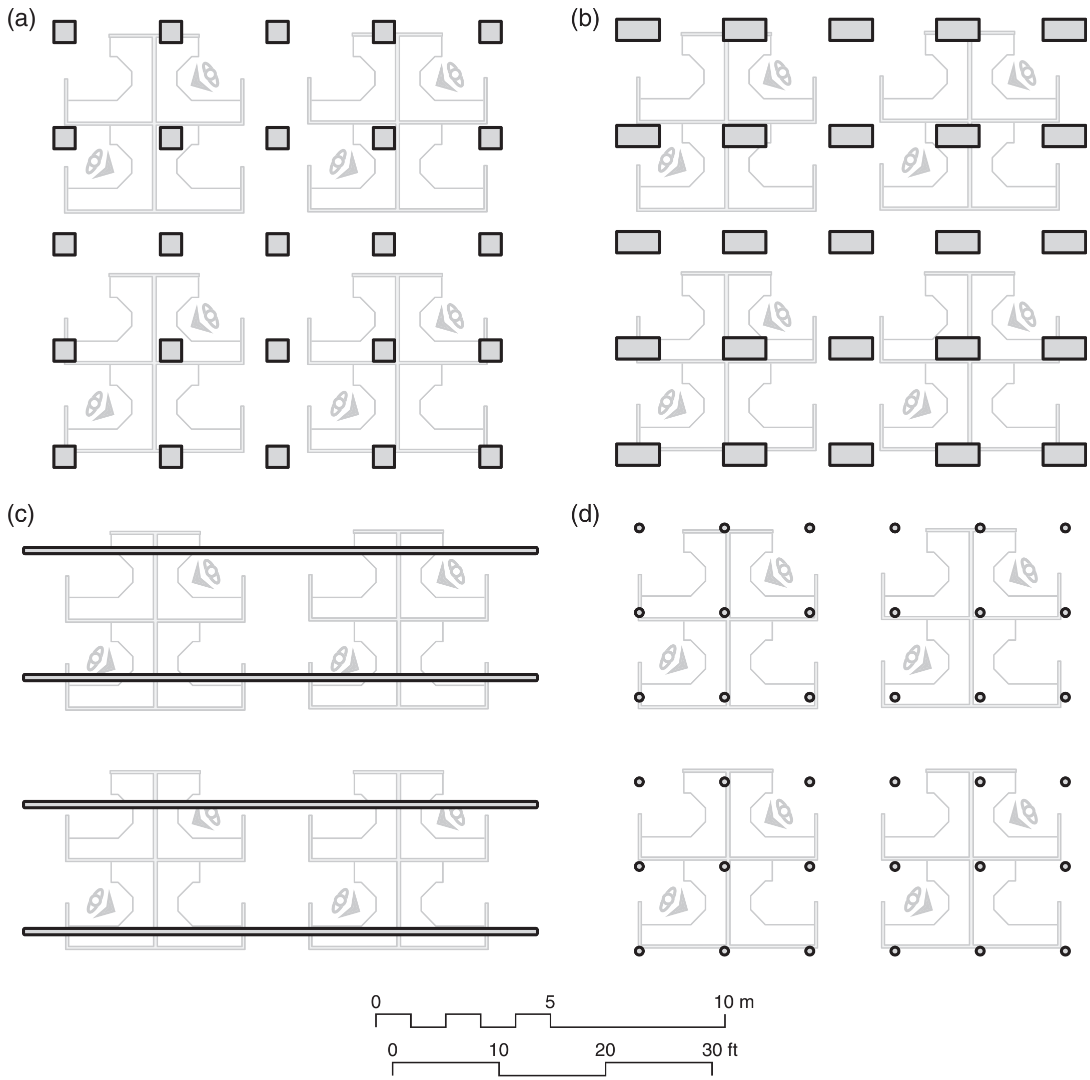


Figure 2 The layouts for the luminaires modelled in the photometric simulation: (a) 2 × 2 troffer, 10′ × 10′ layout (3 m × 3 m; 10 ft ×10 ft); (b) 2 × 4 troffer 10′ × 10′ layout (3 m × 3 m; 10 ft ×10 ft); (c) linear pendant (all types), 12′ layout (spaced apart at 3.7 m; 12 ft); (d) downlight, 8′ × 8′ (2.4 m × 2.4 m; 8 ft × 8 ft) layout. The modelled space measured 16.8 m × 14.6 m (55 ft × 48 ft) with a 2.7 m (9 ft) high ceiling and was furnished with four workstations, each consisting of a cluster of four desks (16 desks total). Eight modelled occupants were distributed throughout the office in the same position for all luminaire layouts. The 2 × 2 troffer, 8′ × 8′ layout (2.4 m × 2.4 m; 8 ft × 8 ft) is not shown here

The two representative luminous intensity distributions modelled for each luminaire type, typical (often Lambertian) and wide (Figure 3), were chosen by the authors from published IES files for a selection of commercially available luminaires. Both luminous intensity distributions were used for six SPDs covering a range of correlated colour

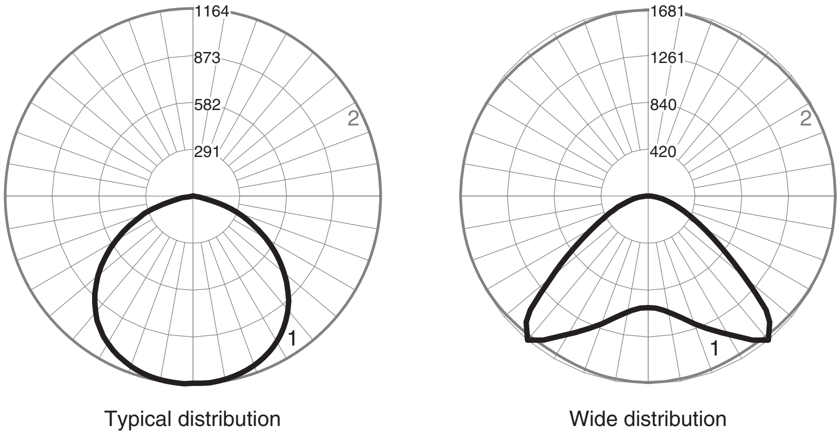


Figure 3 A typical lambertion intensity distribution (left) is generally used to provide uniform illumination on the horizontal work plane, whereas a wider intensity distribution (right) delivers a higher E_V/E_H ratio resulting in more light at the eye and therefore more CS per Watt. Note that, to avoid discomfort glare, light is not emitted at higher angles

temperatures (i.e. CCTs of 2700 K, 3000 K, 3500 K, 4000 K, 5000 K and 6500 K), each delivering E_H levels of 300 lx and 500 lx, resulting in 144 unique lighting conditions (i.e. six luminaire types × two luminous intensity distributions × six CCTs × two E_H values). To document the variations in CS delivery that can occur between different SPDs with the same CCT, the simulation also compared CS calculations for eight SPDs provided by different LED package manufactures using the 2 × 2 troffer at 3000 K and an E_H of 300 lx.

In addition to these six luminaire configurations, the study also modelled the typical 2 × 2 troffer (E_H of 300 lx or 500 lx, CCT of 3000 K and typical luminous intensity distribution) supplemented by the desktop luminaire developed by the LRC, which was included in the LPD calculations. The physical desktop device (62 cm long × 18 cm high × 19 cm deep) is composed of two fully tuneable spectrum, 30 cm linear luminaires (model G2, Ketra, Austin, TX, USA) placed end to end and housed in a wooden frame covered by a domed white acrylic light diffuser (Utilitech Pro Wrap shop light, Lowe's, Mooresville, NC, USA). It is driven by a satellite link controller (Ketra, model N3) with a touchpad interface (Ketra, model X1). For the simulation, the desktop luminaire was configured to deliver either 25 lx (CS = 0.4) or 14 lx (CS = 0.3) of narrow-band, short wavelength ('blue') light (λ_{max} = 470 nm; full width at half maximum (FWHM) = 31 nm) or 50 lx (CS = 0.0) of long wavelength ('red') light (λ_{max} = 634 nm; FWHM = 22 nm) at the modelled occupants' eye level. Red light does not affect the human melatonin rhythm[28,29] and has been demonstrated to provide an alerting stimulus that can help to ameliorate the afternoon decline in alertness known as the post-lunch dip.[30] This solution can also be used in facilities whose personnel follow 24-hour shift schedules, such as healthcare facilities or emergency/customer service call centres, because it can promote alertness without affecting melatonin levels.

While the 144 simulated conditions for the six luminaire types operated at the same output for the entire 'workday' (i.e. 07:00–18:00), four different CS-dosage schedules were modelled for the 2 × 2 and 2 × 4 troffers with and without the supplemental desktop luminaire. The first, baseline schedule provided a CS of 0.3 all day (i.e. 07:00–18:00) using only the 2×2 troffer at an E_H of 500 lx. The second schedule provided a CS of 0.3 all day using the 2×2 troffer at an E_H of 300 lx in combination with the desktop luminaire delivering an E_V of 14 lx of the blue light. The third schedule, a variable dosage providing a CS of 0.4 in the morning (i.e. 07:00–12:00) followed by a lower CS of 0.2 in the afternoon (i.e. 12:00–18:00), used the 2×2 troffer at an E_H of 300 lx supplemented by the desktop luminaire providing an E_V of 25 lx of blue light in the morning, and an E_V of 50 lx of red light in the afternoon. The fourth schedule was similar to the first schedule, but with the 2×4 troffer luminaire providing an E_H of 300 lx and 6500 K delivering a CS of 0.3 for the entire workday. Since the photometric simulation could not evaluate the alerting effect of the red light condition, the 2×2 troffer supplemented by the desktop luminaire conditions were evaluated solely on the basis of total energy used (in $Wh/ft^2/day$).

2.3. Data analyses

The calculations performed for the six different luminaire types used the same SPDs. Using the standard SPDs and the photopic illuminance values (E_V) obtained at the eyes of the simulated occupants in the photometric model, several outcome measures and lighting metrics were calculated. Circadian light (CL_A) and CS were calculated using the Rea *et al.* model of circadian phototransduction,[7,20,22] which is based in part on the light-induced melatonin suppression data from Brainard *et al.*[5] and Thapan *et al.*[6] The CS metric uses the spectral irradiance distribution of light incident at the cornea to calculate CL_A, which is irradiance at the cornea weighted to reflect the spectral sensitivity of the human circadian system. The resulting CL_A value is then used to determine a CS value, which is equivalent to the percent nocturnal melatonin suppression achieved after a 1-hour exposure to the light stimulus from threshold ($CS \approx 0.1$), to saturation ($CS \approx 0.7$). (Lighting professionals are encouraged to use the LRC's web-based CS Calculator to aid in the selection of light sources and light levels that will increase the potential for circadian-effective light exposure in architectural spaces.) Previous research has established that the human circadian system is maximally sensitive to short-wavelength light, with a peak spectral sensitivity near 460 nm, whereas visual acuity, as characterized by the photopic luminous efficiency function (V_λ), has a peak spectral sensitivity of 555 nm (Figure 4).[5–7]

To model any potential relationships between the CS/LPD and E_V/E_H ratios, linear regression analyses were employed using Excel (version 2016, Microsoft Corporation, Redmond, WA, USA). To facilitate comparison of this study's primary metric (i.e. CS) and outcome measure (i.e. CS/LPD ratio) to other lighting metrics, α-opic irradiances were calculated for each of the lighting configurations using the International Commission on Illumination's (CIE) SI-compliant version[31,32] of the Lucas *et al.* Irradiance Toolbox.[16] The α-opic values, reported in $\mu W/cm^{-2}$, represent the response to light stimulus measured for each human photoreceptor (i.e. rods, cones and ipRGCs). The spectral irradiance distributions of the light stimuli were weighted to the respective action spectra (normalized to a value of one at the peak) of each of the photoreceptors in order to calculate the α-opic irradiance values.

In addition to these α-opic irradiance values, EML and 'melanopic illuminance' to photopic illuminance (M/P) ratios were calculated for each of the lighting configurations. The EML metric is a photometric quantity derived from the relative spectral sensitivity of melanopsin, the photopigment expressed in the ipRGCs. The melanopsin

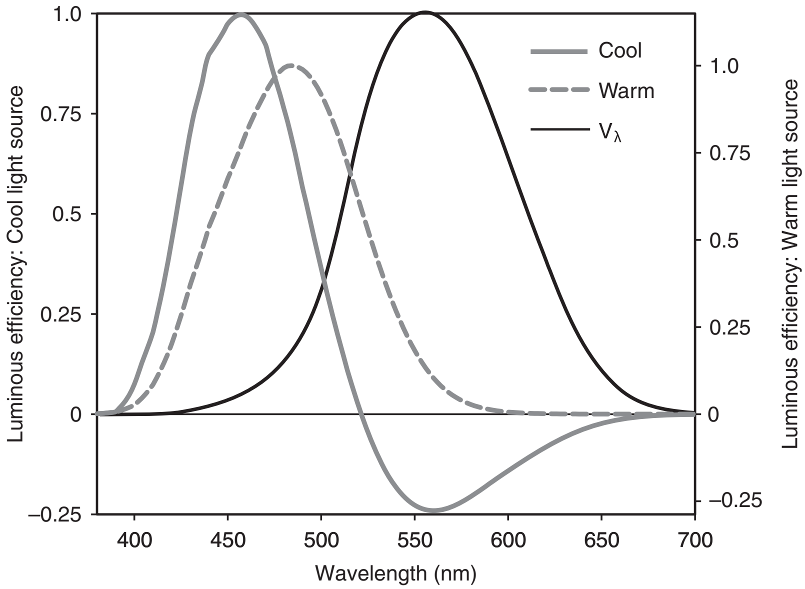


Figure 4 Circadian light (CL_A) is determined by these spectral weighting functions for cool and warm light sources. For more information about how to derive these efficiency functions see Rea *et al.*[20]

action spectrum, with a peak wavelength at approximately 480 nm, is used to weight a light source's spectral irradiance distribution and transform it into a photometric unit that characterizes the photoreceptors' response to the stimulus.[16,33] The M/P ratio reflects a light source's absolute spectral irradiance weighted by the melanopic spectral efficiency function, divided by its absolute spectral irradiance weighted by the CIE photopic luminous efficiency function (V_λ).[34] Since M/P ratios (expressed as a decimal percentage) are not affected by changes in light levels and the same SPDs were used for each CCT for all lighting configurations, it was expected that the resulting M/P ratios for the six luminaire types, illuminances and luminous intensity distributions would be equivalent between the lighting configurations.

2.4. Discomfort glare

In addition to investigating the four strategies for maximizing the CS/LPD ratio, discomfort glare was estimated for the ceiling luminaires that were considered most likely to cause glare. Hence, the luminaires with the highest total lumen output, smallest aperture and direct-only luminous intensity distributions at an E_H of 500 lx (i.e. the 2 × 4 troffer at 3500 K, recessed downlight at 3000 K, and direct pendant at 4000 K) were evaluated to determine whether they would produce uncomfortable amounts of glare for the modelled occupants in the space. The spectral properties of the luminaires were not considered in the discomfort glare calculations.

Discomfort glare was calculated using a method that was originally developed by LRC researchers for evaluating exterior lighting systems.[35] This method, which was revised and tailored for indoor lighting environments, employed the following process. First, direct illuminance was measured from the source (i.e. at the observer's eye viewing the luminaire at an approximate 45° angle from horizontal), followed by measurement of the illuminance of the 10° surround of the source and the ambient illumination in the space. All three measurements were used to calculate the discomfort glare (DG value) following equation (1)[35]

$$DG = \log(E_L + E_S) + 0.6\log\left(\frac{E_L}{E_S}\right) - 0.5\log(E_A) \quad (1)$$

where
DG is the discomfort glare value;
E_L is the direct illuminance from the source;
E_S is the surround illuminance;
E_A is the ambient illuminance.

The luminance of the light source in the direction of the observer was then calculated and the DG value was converted to a De Boer scale rating following equation (2)[36]

$$DB = 6.6 - 6.4\log DG + 1.4\log\left(\frac{50,000}{L_L}\right) \quad (2)$$

where
DB is the De Boer scale rating;
DG is discomfort glare value;
L_L is luminance of the source.

3. Results

3.1. Photometric simulation

The photometric simulation results for the study's 144 discrete lighting configurations employed for the six luminaire types (i.e. 2 × 2 troffer, 2 × 4 troffer, direct linear pendant, direct/indirect linear pendant, indirect linear pendant and recessed downlight) are shown in Table 1. Except for the configuration of the 2 × 4 troffer with a wide distribution at 6500 K, none of the lighting conditions was capable of achieving the design target CS of 0.4—without supplemental light from the desktop luminaire—when the overhead lighting was set at an E_H of 300 lx. Except for the recessed downlight luminaire, all other configurations that delivered an E_H of 500 lx at 6500 K, regardless of luminous intensity distribution, reached the design target CS of 0.4. The troffers and pendants with a direct lighting component generally provided the highest CS/LPD ratios.

Variations in SPD had only a nominal effect on CS/LPD ratios, in that those providing a CS of 0.3 at 5000 K (regardless of E_H levels) yielded a mean LPD that was approximately 5% lower than that for luminaires providing the same CS at 3000 K. Illuminances, on the other hand, played a far greater role than adjustments to SPD in meeting the criterion CS of 0.3 for the simulated lighting conditions that achieved that goal using CCTs between 3000 K and 5000 K (Table 2). By increasing the CCT to 6500 K, all but one of the simulated lighting conditions at either E_H level achieved the criterion CS of 0.3.

In respect to the CS performance for eight different manufacturer's SPDs providing an E_H of 300 lx at the same CCT of 3000 K, the photometric simulation showed a range of CS from 0.22 to 0.26, indicating that, for the same nominal CCT, it is possible to increase CS by selecting an SPD that is better matched to the spectral response of the circadian system.

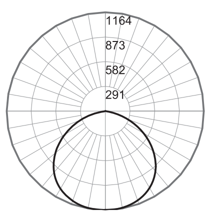
The supplemental desktop luminaire was capable of delivering the design target CS of 0.4 if used in combination with any of the analysed simulated overhead lighting layouts. At full light output, the desktop luminaire providing blue light had a power demand of 18.2 W and delivered a total CS of 0.51 at a distance of 46 cm from the eye. Since the desktop luminaire's full output was not required to reach the CS target in the simulation, it was dimmed to reduce power and provide CS levels of 0.3 and 0.4 in

Table 1 Results for both the typical and wide luminous intensity distributions for each luminaire type (one per page), lumen output, power demand, luminaire spacing and lighting power density (LPD)

2 × 2 Troffer

Typical Distribution

	300 lux horizontal	500 lux horizontal
Output	3284 lm	3284 lm
Power	32.5 W	32.5 W
Spacing	10’ × 10’	8’ × 8’
LPD	0.31 W/ft² (3.34 W/m²)	0.45 W/ft² (4.84 W/m²)



$E_V/E_H = 0.71$

300 lux horizontal

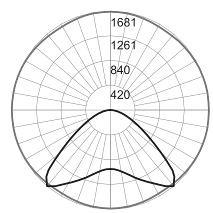
CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	247	263	268	276	289	300
E_V	182	194	198	204	213	221
CL_A	148	194	98	153	226	329
CS	0.19	0.24	0.14	0.20	0.26	**0.33**
CS/LPD	0.62	0.77	0.44	0.64	0.85	1.08
Melanopsin	9	12	14	17	21	27
Rod	14	17	19	22	26	32
S-Cone	3	6	8	10	14	16
M-Cone	24	26	28	30	33	36
L-Cone	31	33	34	34	36	38
EML	78	100	119	143	175	228
M/P	0.43	0.52	0.60	0.70	0.82	1.03

500 lux horizontal

CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	441	469	479	493	516	535
E_V	296	315	321	331	347	359
CL_A	241	316	161	252	370	540
CS	0.28	**0.33**	0.21	0.28	**0.36**	**0.43**
CS/LPD	0.62	0.73	0.46	0.64	0.80	0.96
Melanopsin	15	20	23	28	34	44
Rod	23	28	31	36	43	52
S-Cone	6	9	12	17	22	27
M-Cone	38	43	45	48	53	58
L-Cone	51	54	55	56	58	61
EML	127	162	193	233	284	370
M/P	0.43	0.52	0.60	0.70	0.82	1.03

Wide Distribution

	300 lux horizontal	500 lux horizontal
Output	3600 lm	3600 lm
Power	37 W	37 W
Spacing	10’ × 10’	8’ × 8’
LPD	0.35 W/ft² (3.77 W/m²)	0.51 W/ft² (5.49 W/m²)



$E_V/E_H = 0.72$

300 lux horizontal

CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	275	293	299	307	322	334
E_V	204	217	222	228	239	248
CL_A	166	218	110	172	253	369
CS	0.21	0.26	0.15	0.22	0.29	**0.36**
CS/LPD	0.60	0.73	0.43	0.62	0.81	1.01
Melanopsin	10	13	16	19	24	31
Rod	16	19	22	25	29	36
S-Cone	4	6	9	11	15	18
M-Cone	27	29	31	33	37	40
L-Cone	35	37	38	39	40	42
EML	87	112	133	160	196	255
M/P	0.43	0.52	0.60	0.70	0.82	1.03

500 lux horizontal

CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	488	519	530	545	571	592
E_V	335	356	363	374	392	406
CL_A	273	357	182	285	420	612
CS	**0.30**	**0.35**	0.23	**0.31**	**0.38**	**0.45**
CS/LPD	0.59	0.69	0.45	0.61	0.75	0.89
Melanopsin	17	22	26	32	39	50
Rod	26	31	35	41	48	59
S-Cone	6	10	14	19	25	30
M-Cone	43	48	51	55	60	66
L-Cone	57	61	62	63	66	69
EML	143	183	218	263	321	418
M/P	0.43	0.52	0.60	0.70	0.82	1.03

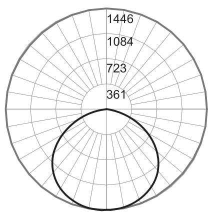
(continued)

Table 1 Continued

2 × 4 Troffer

Typical Distribution

	300 lux horizontal	500 lux horizontal
Output	4221 lm	5089 lm
Power	30.5 W	50.3 W
Spacing	10' × 10'	10' × 10'
LPD	0.29 W/ft² (3.12 W/m²)	0.48 W/ft² (5.17 W/m²)



$E_V/E_H = 0.74$

300 lux horizontal

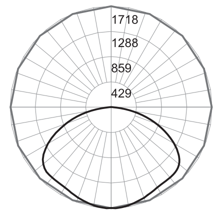
CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	316	336	343	353	370	383
E_V	235	250	255	262	275	285
CL_A	191	250	127	199	292	426
CS	0.23	0.28	0.17	0.24	**0.31**	**0.38**
CS/LPD	0.81	0.98	0.58	0.83	1.08	1.33
Melanopsin	12	15	18	22	27	35
Rod	18	22	25	29	34	41
S-Cone	5	7	10	13	17	21
M-Cone	30	34	36	38	42	46
L-Cone	40	43	43	44	46	48
EML	100	129	153	185	225	293
M/P	0.43	0.52	0.60	0.70	0.82	1.03

500 lux horizontal

CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	379	403	411	423	443	459
E_V	281	299	305	314	329	341
CL_A	229	300	152	239	351	512
CS	0.27	**0.32**	0.20	0.27	**0.35**	**0.42**
CS/LPD	0.56	0.66	0.41	0.57	0.73	0.88
Melanopsin	14	19	22	27	32	42
Rod	22	26	30	34	41	50
S-Cone	5	9	12	16	21	25
M-Cone	37	40	43	46	50	55
L-Cone	48	51	52	53	55	58
EML	120	154	183	221	270	351
M/P	0.43	0.52	0.60	0.70	0.82	1.03

Wide Distribution

	300 lux horizontal	500 lux horizontal
Output	4519 lm	5710 lm
Power	48.8 W	65 W
Spacing	10' × 10'	10' × 10'
LPD	0.46 W/ft² (4.95 W/m²)	0.62 W/ft² (6.67 W/m²)



$E_V/E_H = 0.78$

300 lux horizontal

CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	325	345	352	363	380	394
E_V	254	271	276	284	298	309
CL_A	207	271	137	215	317	462
CS	0.25	**0.30**	0.18	0.26	**0.33**	**0.40**
CS/LPD	0.54	0.64	0.39	0.55	0.71	0.86
Melanopsin	13	17	20	24	29	38
Rod	20	24	27	31	37	45
S-Cone	5	8	11	14	19	23
M-Cone	33	37	39	42	46	50
L-Cone	44	46	47	48	50	52
EML	109	139	166	200	244	318
M/P	0.43	0.52	0.60	0.70	0.82	1.03

500 lux horizontal

CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	411	437	445	459	480	498
E_V	321	342	349	359	376	390
CL_A	262	342	175	274	402	587
CS	0.29	**0.34**	0.22	**0.30**	**0.37**	**0.44**
CS/LPD	0.47	0.55	0.35	0.48	0.60	0.72
Melanopsin	16	21	25	30	37	48
Rod	25	30	34	39	46	57
S-Cone	6	10	13	18	24	29
M-Cone	42	46	49	53	58	63
L-Cone	55	58	59	61	63	66
EML	137	176	209	252	308	401
M/P	0.43	0.52	0.60	0.70	0.82	1.03

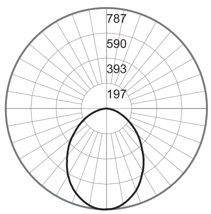
(continued)

Table 1 Continued

Direct Linear Pendant

Typical Distribution

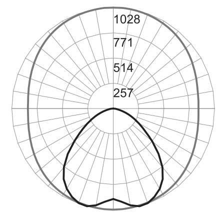
	300 lux horizontal	500 lux horizontal
Output	413 lm/ft	616 lm/ft
Power	8 W/ft	10.1 W/ft
Spacing	12'	12'
LPD	0.58 W/ft² (6.24 W/m²)	0.74 W/ft² (7.97 W/m²)



$E_V/E_H = 0.53$

Wide Distribution

	300 lux horizontal	500 lux horizontal
Output	446 lm/ft	660 lm/ft
Power	4.75 W/ft	7 W/ft
Spacing	12'	12'
LPD	0.58 W/ft² (6.24 W/m²)	0.51 W/ft² (5.49 W/m²)



$E_V/E_H = 0.55$

300 lux horizontal

Typical 2700 K	Typical 3000 K	Typical 3500 K	Typical 4000 K	Typical 5000 K	Typical 6500 K	CCT	Wide 2700 K	Wide 3000 K	Wide 3500 K	Wide 4000 K	Wide 5000 K	Wide 6500 K
336	357	364	375	393	407	E_H	349	371	378	389	408	423
180	192	195	201	211	218	E_V	190	202	206	212	222	231
147	192	97	151	223	325	CL_A	155	203	102	160	235	343
0.19	0.24	0.13	0.20	0.26	**0.33**	CS	0.20	0.24	0.14	0.21	0.27	**0.34**
0.33	0.40	0.23	0.34	0.45	0.57	CS/LPD	0.57	0.70	0.41	0.59	0.78	0.99
9	12	14	17	21	27	Melanopsin	10	13	15	18	22	29
14	17	19	22	26	32	Rod	15	18	20	23	27	34
3	6	8	10	13	16	S-Cone	4	6	8	11	14	17
23	26	27	29	32	36	M-Cone	25	27	29	31	34	38
31	33	33	34	35	37	L-Cone	33	35	35	36	37	39
77	99	117	141	173	225	EML	81	104	124	149	182	237
0.43	0.52	0.60	0.70	0.82	1.03	M/P	0.43	0.52	0.60	0.70	0.82	1.03

500 lux horizontal

Typical 2700 K	Typical 3000 K	Typical 3500 K	Typical 4000 K	Typical 5000 K	Typical 6500 K	CCT	Wide 2700 K	Wide 3000 K	Wide 3500 K	Wide 4000 K	Wide 5000 K	Wide 6500 K
493	524	535	550	577	598	E_H	516	549	560	576	604	626
261	277	283	291	305	316	E_V	281	299	305	314	329	341
212	278	141	221	325	474	CL_A	229	300	152	239	351	512
0.25	**0.30**	0.19	0.26	**0.33**	**0.41**	CS	0.27	**0.32**	0.20	0.27	**0.35**	**0.42**
0.34	0.41	0.25	0.35	0.45	0.55	CS/LPD	0.52	0.62	0.39	0.54	0.68	0.82
13	17	20	25	30	39	Melanopsin	14	19	22	27	32	42
20	24	28	32	38	46	Rod	22	26	30	35	41	50
5	8	11	15	19	24	S-Cone	5	9	12	16	21	25
34	37	40	43	47	51	M-Cone	37	40	43	46	50	56
45	47	48	49	51	54	L-Cone	48	51	52	53	55	58
111	143	170	205	250	326	EML	120	154	183	221	270	352
0.43	0.52	0.60	0.70	0.82	1.03	M/P	0.43	0.52	0.60	0.70	0.82	1.03

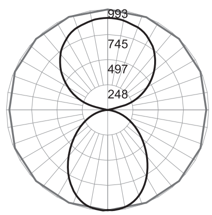
(continued)

Table 1 Continued

Direct/Indirect Linear Pendant

Typical Distribution

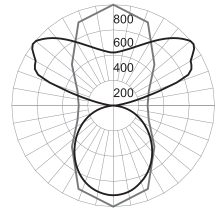
	300 lux horizontal	500 lux horizontal
Output	506 lm/ft	758 lm/ft
Power	5.13 W/ft	7.7 W/ft
Spacing	12’	12’
LPD	0.37 W/ft² (3.98 W/m²)	0.56 W/ft² (6.03 W/m²)



$E_V/E_H = 0.60$

Wide Distribution

	300 lux horizontal	500 lux horizontal
Output	490 lm/ft	817 lm/ft
Power	4.3 W/ft	7.2 W/ft
Spacing	12’	12’
LPD	0.31 W/ft² (3.34 W/m²)	0.52 W/ft² (5.60 W/m²)



$E_V/E_H = 0.62$

300 lux horizontal

Typical: 2700 K	3000 K	3500 K	4000 K	5000 K	6500 K	CCT	Wide: 2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
303	322	329	338	354	367	E_H	285	304	310	319	334	346
180	192	196	201	211	219	E_V	176	187	191	197	206	214
147	192	97	152	223	325	CL_A	143	188	94	148	218	318
0.19	0.24	0.13	0.20	0.26	**0.33**	CS	0.19	0.23	0.13	0.19	0.26	**0.33**
0.51	0.63	0.36	0.52	0.70	0.89	CS/LPD	0.60	0.74	0.42	0.61	0.82	1.04
9	12	14	17	21	27	Melanopsin	9	12	14	17	20	26
14	17	19	22	26	32	Rod	14	16	19	22	25	31
3	6	8	10	13	16	S-Cone	3	5	7	10	13	16
23	26	27	29	32	36	M-Cone	23	25	27	29	32	35
31	33	33	34	36	37	L-Cone	30	32	33	33	35	36
77	99	117	142	173	225	EML	75	97	115	138	169	220
0.43	0.52	0.60	0.70	0.82	1.03	M/P	0.43	0.52	0.60	0.70	0.82	1.03

500 lux horizontal

Typical: 2700 K	3000 K	3500 K	4000 K	5000 K	6500 K	CCT	Wide: 2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
454	483	493	507	532	551	E_H	476	506	516	531	557	577
270	288	293	302	316	328	E_V	294	312	319	328	344	356
220	288	146	229	337	492	CL_A	239	313	159	250	367	535
0.26	**0.31**	0.19	0.27	**0.34**	**0.41**	CS	0.27	**0.33**	0.20	0.28	**0.36**	**0.43**
0.46	0.55	0.34	0.47	0.60	0.73	CS/LPD	0.52	0.62	0.39	0.54	0.68	0.82
14	18	21	26	31	41	Melanopsin	15	19	23	28	34	44
21	25	29	33	39	48	Rod	23	27	31	36	42	52
5	8	11	15	20	24	S-Cone	6	9	12	16	22	27
35	39	41	44	49	53	M-Cone	38	42	45	48	53	58
46	49	50	51	53	56	L-Cone	50	53	54	56	58	61
115	148	176	212	259	338	EML	125	161	191	231	282	367
0.43	0.52	0.60	0.70	0.82	1.03	M/P	0.43	0.52	0.60	0.70	0.82	1.03

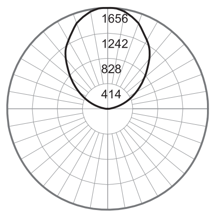
(continued)

Table 1 Continued

Indirect Linear Pendant

Typical Distribution

	300 lux horizontal	500 lux horizontal
Output	791 lm/ft	988 lm/ft
Power	12.5 W/ft	18 W/ft
Spacing	12’	12’
LPD	0.91 W/ft^2 (9.80 W/m^2)	1.32 W/ft^2 (14.21 W/m^2)



$E_V/E_H = 0.66$

300 lux horizontal

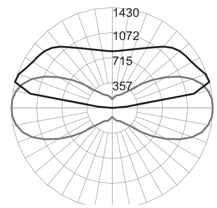
CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	350	372	380	391	410	424
E_V	231	245	250	258	270	280
CL_A	188	246	124	195	287	418
CS	0.23	0.28	0.17	0.24	**0.31**	**0.38**
CS/LPD	0.25	0.31	0.18	0.26	0.34	0.42
Melanopsin	12	15	18	22	27	35
Rod	18	22	24	28	33	41
S-Cone	4	7	10	13	17	21
M-Cone	30	33	35	38	41	46
L-Cone	40	42	43	44	45	48
EML	99	126	150	181	221	288
M/P	0.43	0.52	0.60	0.70	0.82	1.03

500 lux horizontal

CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	437	465	475	489	512	531
E_V	288	307	313	322	337	350
CL_A	235	307	156	245	360	525
CS	0.27	**0.32**	0.20	0.28	**0.35**	**0.42**
CS/LPD	0.21	0.24	0.15	0.21	0.27	0.32
Melanopsin	15	19	23	27	33	43
Rod	22	27	31	35	42	51
S-Cone	6	9	12	16	21	26
M-Cone	37	41	44	47	52	57
L-Cone	49	52	53	55	57	59
EML	123	158	188	226	276	360
M/P	0.43	0.52	0.60	0.70	0.82	1.03

Wide Distribution

	300 lux horizontal	500 lux horizontal
Output	740 lm/ft	1036 lm/ft
Power	6.75 W/ft	9.75 W/ft
Spacing	12’	12’
LPD	0.49 W/ft^2 (5.27 W/m^2)	0.71 W/ft^2 (7.64 W/m^2)



$E_V/E_H = 0.68$

300 lux horizontal

CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	325	346	353	363	381	395
E_V	220	234	239	246	258	267
CL_A	179	235	119	186	274	399
CS	0.22	0.27	0.16	0.23	**0.30**	**0.37**
CS/LPD	0.45	0.55	0.33	0.47	0.61	0.75
Melanopsin	11	15	17	21	25	33
Rod	17	21	23	27	32	39
S-Cone	4	7	9	12	16	20
M-Cone	29	32	34	36	40	43
L-Cone	38	40	41	42	43	45
EML	94	121	143	173	211	275
M/P	0.43	0.52	0.60	0.70	0.82	1.03

500 lux horizontal

CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
E_H	456	485	494	509	533	553
E_V	309	328	335	345	361	374
CL_A	251	329	168	263	386	563
CS	0.28	**0.33**	0.21	0.29	**0.37**	**0.44**
CS/LPD	0.40	0.47	0.30	0.41	0.51	0.61
Melanopsin	16	20	24	29	36	46
Rod	24	29	33	38	45	54
S-Cone	6	10	13	17	23	28
M-Cone	40	44	47	50	55	61
L-Cone	53	56	57	58	61	64
EML	132	169	201	242	296	385
M/P	0.43	0.52	0.60	0.70	0.82	1.03

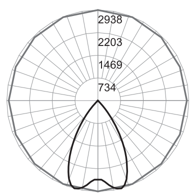
(continued)

Table 1 Continued

Downlight

Typical Distribution

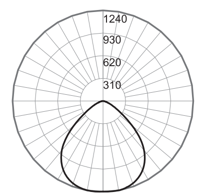
	300 lux horizontal	500 lux horizontal
Output	1951 lm	2880 lm
Power	23.5 W	36.8 W
Spacing	8' × 8'	8' × 8'
LPD	0.32 W/ft² (3.44 W/m²)	0.50 W/ft² (5.38 W/m²)



$E_V/E_H = 0.41$

Wide Distribution

	300 lux horizontal	500 lux horizontal
Output	1868 lm	2678 lm
Power	33.9 W	34.9 W
Spacing	8' × 8'	8' × 8'
LPD	0.46 W/ft² (4.95 W/m²)	0.59 W/ft² (6.35 W/m²)



$E_V/E_H = 0.58$

300 lux horizontal (Typical Distribution | Wide Distribution)

2700 K	3000 K	3500 K	4000 K	5000 K	6500 K	CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
335	357	364	375	393	407	E_H	280	297	303	312	327	339
137	146	148	153	160	166	E_V	162	172	176	181	190	196
111	146	73	115	169	246	CL_A	132	173	87	136	200	292
0.15	0.19	0.10	0.16	0.21	0.28	CS	0.18	0.22	0.12	0.18	0.24	**0.31**
0.47	0.59	0.32	0.48	0.66	0.87	CS/LPD	0.38	0.47	0.26	0.39	0.52	0.67
7	9	11	13	16	21	Melanopsin	8	11	13	15	19	24
11	13	14	17	20	24	Rod	13	15	17	20	23	29
3	4	6	8	10	12	S-Cone	3	5	7	9	12	15
18	20	21	22	25	27	M-Cone	21	23	25	26	29	32
23	25	25	26	27	28	L-Cone	28	29	30	31	32	33
58	75	89	107	131	171	EML	69	89	105	127	155	202
0.43	0.52	0.60	0.70	0.82	1.03	M/P	0.43	0.52	0.60	0.70	0.82	1.03

500 lux horizontal (Typical Distribution | Wide Distribution)

2700 K	3000 K	3500 K	4000 K	5000 K	6500 K	CCT	2700 K	3000 K	3500 K	4000 K	5000 K	6500 K
495	527	537	553	579	600	E_H	396	422	430	443	464	481
202	215	219	225	236	245	E_V	234	249	254	261	274	284
164	215	108	170	250	365	CL_A	191	249	126	198	291	424
0.21	0.26	0.15	0.21	0.28	**0.35**	CS	0.23	0.28	0.17	0.24	**0.31**	**0.38**
0.42	0.51	0.29	0.43	0.56	0.70	CS/LPD	0.49	0.59	0.35	0.50	0.65	0.80
10	13	16	19	23	30	Melanopsin	12	15	18	22	27	35
16	19	21	25	29	36	Rod	18	22	25	29	34	41
4	6	8	11	15	18	S-Cone	4	7	10	13	17	21
26	29	31	33	36	40	M-Cone	30	34	36	38	42	46
35	37	37	38	40	42	L-Cone	40	43	43	44	46	48
86	111	131	159	193	252	EML	100	128	152	184	224	292
0.43	0.52	0.60	0.70	0.82	1.03	M/P	0.43	0.52	0.60	0.70	0.82	1.03

Note: A polar candela plot and E_V/E_H ratio are shown for each luminous intensity distribution. The results include the values calculated for both the E_H of 300 lx and 500 lx conditions at correlated colour temperatures (CCTs) ranging from 2700 K to 6500 K for the following parameters: average horizontal illuminance (E_H); average vertical illuminance (E_V); average circadian light (CL_A); average circadian stimulus (CS); circadian stimulus/lighting power density ratio (CS/LPD); CIE α-opic responses for the ipRGCs (melanopsin), rod and the three cone type photopigments; equivalent melanopic lux (EML); and 'melanopic illuminance' to photopic illuminance (V_λ) ratios (M/P). The CS values that reach or exceed the criterion CS of 0.3 are bordered in bold for ease of identification.

Table 2 The number and percentage of simulations at the same CCT, and target illuminance (12 in total) that were capable of providing an average circadian stimulus (CS) of 0.3 or greater

E_H level (lx)	Simulated lighting conditions with CS of 0.3											
	2700 K		3000 K		3500 K		4000 K		5000 K		6500 K	
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%
300	0	0	1	8.3	0	0	0	0	4	33.3	11	91.7
500	1	8.3	10	83.3	0	0	2	16.7	11	91.7	12	100

Note: The percentage of luminaires providing the criterion CS of 0.3 is more significantly increased by increasing the light level from 300 lx to 500 lx than by adjusting the CCT from 3000 K to 5000 K. Except for a single lighting condition, increasing the CCT to 6500 K successfully achieved the criterion CS of 0.3 at either E_H level.

Table 3 Total daily lighting energy for the four dosage schedule options that achieved the targeted CS. The 3000 K, 2 × 2 troffer only scenario targeting a CS of 0.4 in the morning and a CS of 0.2 in the afternoon did not reach the desired targets

Scenario	Dosage schedule (CS, time of day)	Overhead lighting		Desktop luminaire		Total daily lighting energy use	
		Distribution	Target E_H	Colour	E_V	(Wh/ft^2/day)	Wh/m^2/day
3000 K 2 × 2 troffer							
Overhead only	CS = 0.3, 07:00–18:00	Typical	500	–	–	4.91	52.85
With desktop luminaire	CS = 0.3, 07:00–18:00	Typical	300	Blue	14	3.85	41.44
	CS = 0.4, 07:00–12:00	Typical	300	Blue	25	4.24	45.64
	CS = 0.2, 12:00–18:00			Red	50		
6500 K 2 × 4 troffer							
Overhead only	CS = 0.3, 07:00–18:00	Typical	300	–	–	3.19	34.34

Note: The first table row for the desktop luminaire shows the fixed schedule dosage (CS of 0.3) for the entire day. The second and third table rows for the desktop luminaire show the variable schedule dosage for the morning (CS of 0.4) and for the afternoon (CS of 0.2).

combination with the 2 × 2 troffer delivering an E_H of 300 lx at 3000 K. When it was set to a level that provided a CS of 0.3, the desktop luminaire delivered an additional 14 lx of blue light, which increased the LPD by 0.04 W/ft^2 (0.43 W/m^2), in addition to the LPD of 0.31 W/ft^2 (3.34 W/m^2) for the 2 × 2 troffer alone. When set to a level that provided a CS of 0.4, the desktop luminaire delivered an additional 25 lx of blue light, which increased the combined lighting's LPD by 0.07 W/ft^2 (0.75 W/m^2). In other words, the desktop luminaire provided a higher CS than that reached by any simulated overhead lighting with CCTs below 6500 K, and did so at a lower LPD than any of the overhead luminaires providing a CS of 0.3.

Of the four CS dosage schedule options analysed in the simulation, the 2 × 4 troffer with an E_H of 300 lx at 6500 K provided a CS of 0.3 for the entire workday while using the lowest amount of total energy (Table 3). Of the two options using the 2 × 2 troffer at 3000 K combined with the desktop luminaire, the one delivering an E_H of 300 lx (overhead lighting) and an E_V of 14 lx of blue light (desktop luminaire) used a lower amount of total energy to achieve a CS of 0.3 for the entire workday. The variable CS dosage schedule providing a CS of 0.4 in the morning and 0.2 in the afternoon did not confer energy savings compared to the option delivering a CS of 0.3 for the entire workday (see Table 3).

3.2. Discomfort glare

The lighting conditions that were considered most likely to cause discomfort at an E_H of 500 lx achieved De Boer ratings ranging from 'satisfactory' or better (i.e. the 2×4 troffer with a De Boer score of 7.9 and recessed downlight with a De Boer score of 8.7) to 'just permissible' (the direct pendant with a De Boer score of 5.8).

4. Discussion

The nominally successful strategy of varying a lighting system's luminous intensity distribution to achieve higher E_V/E_H ratios highlighted the importance of luminaire selection when designing lighting for the human circadian system, which relies on illuminance at the eye (E_V) rather than illuminance on the work plane (E_H). The photometric simulation demonstrated that troffers and linear pendants with at least some direct lighting component are the most effective luminaire types for delivering CS. Yet, unlike the 2×2 troffer and supplemental desktop luminaire that provided high levels of CS using a minimal amount of added energy, with the exception of one wide distribution 2×4 troffer, none of the evaluated lighting systems was capable of providing the design target CS value of 0.4 without exceeding either an E_H of 500 lx or using a CCT of at least 5000 K.

It should be noted that a 5000 K or higher CCT lighting solution for an office environment may not necessarily be the most desirable design choice. If cooler CCTs are not desirable, warmer colour light sources can be used if E_H is increased to 500 lx, which exceeds what the IES typically recommends for most (but not all) tasks in office spaces.[37] In the present study, systems delivering an E_H of 500 lx were overwhelmingly more successful in achieving the desired CS level than those delivering an E_H of only 300 lx. To reduce energy use, the luminaire's luminous intensity distribution should be carefully selected so that E_V/E_H ratios are as high as possible while also ensuring that the higher E_V/E_H ratio does not come at the cost of unacceptable discomfort glare. The calculations presented in this study show that an E_V/E_H ratio of at least 0.65 will permit achieving targeted CS levels while employing lower light levels on the work plane. The calculations presented here also underscore the importance of using SPDs, and not just CCTs, when it comes to selecting light sources for light and health applications, because even within a single CCT, some sources provide CS more effectively than others.

The 2×4 troffer with a wide luminous intensity distribution was not shown to cause glare in our simulation, but as this was not tested in a large-scale human factors study, further evaluation would be needed to determine with more certainty whether this luminaire would be perceived as glaring. A high E_V/E_H ratio can be achieved in various ways apart from employing recessed ceiling lights with a wide distribution. Higher E_V/E_H ratios can also be achieved through the use of vertically oriented light sources and indirect sources that reflect light off room surfaces. Our analyses showed that a higher E_V/E_H ratio is not necessarily directly proportional to higher discomfort glare, but it is correlated with more efficient CS delivery. Regardless, the design process should consider the trade-offs between delivering circadian-effective lighting in an energy-efficient manner and human factors considerations such as glare and preference.

While the more conventional strategies of adjusting luminaire luminous intensity distributions (i.e. increasing E_V/E_H ratios) and optimizing the lighting's SPD (i.e. using higher CCT sources) were somewhat effective for improving CS/LPD ratios, the most impactful strategy involved thinking beyond the ceiling plane and using circadian-effective light sources positioned at eye level. Supplementing common overhead lighting with a desktop luminaire delivering light directly to the simulated office occupants' eyes provided a greater amount of CS at a lower LPD than overhead luminaires that were capable of delivering the criterion CS of 0.3.

The benefits of this strategy were supported by the results from a limited, human factors pilot study that recorded the subjective responses of 20 experimental participants (10 females and 10 males, mean age 33.1 years) to a desktop luminaire delivering an E_V of 30 lx of blue light in combination with a 2×2 troffer providing an E_H of 300 lx for a total CS of 0.3. The participants, who were asked to perform typical computer tasks during the experiment, did not find the desktop luminaire to be glaring (average De Boer rating of 7.6) or in any way uncomfortable. While further research is needed to evaluate discomfort glare from these proposed strategies, these findings support our suggestion that lighting designers should also consider an additional 'layer' of light for non-visual effects to complement the lighting systems required for visual performance, particularly when faced with stringent energy codes and constraints upon light level and/or CCT. Lighting manufacturers should also consider developing new products that can effectively deliver the additional light required to impact the circadian system without increasing energy loads, which includes task lighting options.

The fourth lighting strategy that we investigated, which simulated four different CS dosage schedules, two using overhead lighting alone and two using overhead lighting in combination with the desktop luminaire, successfully delivered the specified CS but did not prove to be effective for reducing energy use. One of those schedules was designed to provide a higher design target CS of 0.4 during the morning hours (i.e. 07:00–12:00) to compensate for a lower CS of 0.2 in the afternoon (i.e. 12:00–18:00), with the desktop luminaire delivering an E_V of 25 lx of blue light in the morning and an E_V of 50 lx of red light in the afternoon to provide an alerting stimulus. However, this variable CS dosage strategy did not result in lower energy use than the combined 2×2 troffer (E_H of 300 lx at a CCT of 3000 K) and desktop luminaire (E_V of 14 lx of blue light) delivering a CS of 0.3 all day (07:00–18:00). The most-effective configuration for reaching the criterion CS of 0.3 with the lowest total energy use was the 2×4 troffer delivering an E_H of 300 lx at 6500 K, though we acknowledge that such a high CCT light source in an office environment might not be acceptable to its occupants due to the illumination's cool tint.[38,39]

It should also be noted that no studies to date have investigated how amount, spectrum and duration of light exposure interact to affect the circadian system. More importantly, there are few data available regarding the reciprocity of the human circadian system response (i.e. the trade-off between duration and amount). The dosage schedules tested here were based on what we currently know about the circadian system's response to light. Morning light advances the timing of the circadian system, and because we have a biological clock that runs with a period slightly greater than 24 hours, we need to advance our clocks daily to maintain entrainment to the 24-hour solar day. Consistently, drawing from a large sample of experimental participants, Roenneberg and Merrow demonstrated that circadian entrainment was associated with a 2-hour exposure to daylight.[40] Taken together, and notwithstanding the limitations of these assumptions, we believe that the dosage schedule used in our simulations is one that could be used to promote circadian entrainment. Given that light will also exert a direct, alerting effect on humans, reducing light levels in the afternoon to save energy may have negative impacts on workers' alertness and should be considered when making design decisions. For that reason, we have been investigating the impact of saturated red light on decreasing the post-lunch dip in alertness.[29]

Although the scientific evidence clearly shows that the response by the circadian system involves all types of photoreceptors, and not just the ipRGC response, designers may still be required to provide 200 EML at the eye if they are compelled to comply with the Well Building Standard.[17] The EML metric has been adopted as the metric of choice for that standard because it is calculated using a relatively straightforward method, but EML is incomplete in the sense that it does not take into account the contribution of the classical photoreceptors, or spectral opponency, in circadian phototransduction.[20,41] Nonetheless, for all of the light sources used in this study, an EML of 250 was always associated with a CS of 0.3 or greater. With a few exceptions, which can be explained by the non-linearity of the CS model due to spectral opponency, an EML between 200 and 250 was associated with a CS of 0.25 or greater. If a lighting designer should choose to work with warmer light sources (i.e. below 3500 K), the melanopsin response and the CS are generally the same.

Limitations in the applicability of this study's results should be noted. The present results do not take into account human factors such as the photic history, or past light exposures, of the occupants of the space. Exposure to high levels of CS late in the evening can counteract the benefits of high levels of CS exposure in the morning hours. In a real-world application, therefore, it is important to gain a reasonably thorough understanding of the behavioural patterns of a space's occupants, as their photic history can have an impact on the efficacy of the circadian lighting design.

It is also noteworthy that the E_V calculations performed in this study employed a virtual cosine-corrected illuminance meter in the photometric simulation software AGi32. In the actual physical world, it should be expected that natural shading of the occupants' eyes will occur due to their facial contours and features (e.g. brow, nose and cheeks), with the likely result of less light reaching the retina. This natural shading, and the shading and absorption of light from non-modelled objects or furniture in the space, can cause actual CS levels to be lower than those calculated in a simulation, and thus justifies a recommended design CS target of 0.4.

The present study's simulation calculated the average illuminance and CS values received by eight occupants of an open office, finding that the troffers and pendants with a direct lighting component generally provided the highest CS/LPD ratios, which for the most part were associated with higher E_V/E_H ratios. This would be expected, of course, given that the delivery of CS is dependent on E_V. It is important to consider, however, that the simulation's layouts were individually optimized between the various luminaire types in order to meet the study's E_H targets while using a minimum number of luminaires. Additionally, each luminaire had a different luminous efficacy (lumens/Watt) that resulted in a low correlation between E_V/E_H ratios and CS/LPD ratios. These considerations, taken together, point to the study's primary aim, which was not to recommend any specific type of luminaire but, rather, was to point out and quantify the impacts of luminaire attributes (e.g. luminous intensity distribution) for delivering CS to office occupants while avoiding increased energy use.

Finally, in an actual physical space, it is more or less certain that some of the occupants would have received less than the average CS, while others received more. Designers should therefore strive to ensure that all occupants of a space receive the required CS dosage and benchmark the performance of their designs on the specific environments' worst-case scenarios (e.g. an occupant in a back corner of a room facing away from any windows). It also should be noted that the luminaires modelled in this study, while representative of real-world products, in no way comprise a comprehensive sample of the existing range and types of available LED luminaires. As such, the present study does not propose a specific luminaire type as being better suited for CS delivery. Rather, we wish to emphasize that any luminaire's performance characteristics should be taken into account, and optimized where possible, to ensure the desired CS levels are delivered in the most efficacious manner possible.

In conclusion, it is our hope that lighting designers and manufacturers use the information presented here as a food for thought that can assist them in creating products and spaces that promote circadian entrainment and alertness while still maintaining the quality of the visual environment.

Acknowledgements

The authors would like to thank Kassandra Gonzalez, Rohan Nagare, Greg Ward and David Pedler for their technical and editorial assistance.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Funding for this study was provided by Natural Resources Canada, the Lighting Research Center's Lighting Energy Alliance (Efficiency Vermont, Energize Connecticut, National Grid, Natural Resources Canada and the Northwest Energy Efficiency Alliance) and the Lighting Research Center's Light and Health Alliance (Acuity Brands, CREE, Current by GE, Ketra, OSRAM, Philips and USAI Lighting).

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