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Correspondence: Designing and specifying light for melatonin suppression, non-visual responses and integrative lighting solutions – establishing a proper bright day, dim night metrology

Further discussion in response to MS Rea, The law of reciprocity holds (more or less) for circadian-effective lighting

The typical human indoor light environment strongly deviates from the natural light–dark cycle outdoors, both in terms of spectrum and amount of light exposure. The ubiquitous availability of electric light enables us to spend large parts of our day indoors, in conditions with limited, or sometimes even without, any natural daylight. Across daytime, we therefore expose ourselves to light conditions that are relatively dim, with daytime illuminances that frequently do not exceed civil twilight on a semi-overcast day,[1] while during the evening and at nighttime the abundant use of electric light deprives us of natural darkness. Consequently, in our 24/7 society, we are exposed to dimmer days, brighter nights and lower day–night contrasts as compared to the natural light–dark cycle outdoors.[2–4] This has negative consequences for our mental and physical health, sleep and performance.[5–7]

The 24-hour light–dark cycle and its light exposure regulate our circadian rhythms and affect our mood, daytime functioning and nighttime sleep. These effects are strongly mediated by a (melanopsin based) photoreceptor that, in humans, is maximally sensitive to the short-wavelength portion of the visible spectrum around 480 nm. This melanopsin-based photoreceptor (often denoted as ipRGC, a shorthand for intrinsically photosensitive Retinal Ganglion Cell) is known to combine its own melanopsin-mediated (i.e. melanopic) response to light with (extrinsic) signals from rod and cone photoreceptors.[8] In 2018, an internationally balloted consensus metrology has been standardized[9] to provide a systematic SI-compliant framework to assess and characterize light levels based on the degree to which they activate each of the five different (α-opic) photoreceptor types (i.e. three kinds of cones, rods and ipRGCs) in the human retina. The metrology comprises five α-opic irradiances and five α-opic equivalent daylight illuminances (α-opic EDIs) that have a direct linear relationship with the luminous and/or radiant flux of a light source. The metrology allows to systematically investigate the extent to which a particular circadian, neuroendocrine or neurobehavioral response to light is driven by a single photoreceptor or by a combination of photoreceptors, and whether this depends, for instance, on the amount, duration or timing of the light exposure.[10,11]

Recently, an international expert workshop on circadian and neurophysiological photometry published a set of light recommendations to best support human physiology, sleep and wakefulness within indoor settings.[12] The workshop concluded that under most practically relevant situations, the spectral sensitivity of non-visual responses to light can be well described by the intrinsic, melanopsin-based, spectral sensitivity

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of ipRGCs. Consequently, the workshop recommendations were expressed in terms of the melanopic EDI, measured at the eye position of the user (with a detector orientation that corresponds to the dominant direction of gaze):

- Throughout the daytime, the recommended minimum melanopic EDI is 250 lx.
- During the evening, starting at least 3 hours before bedtime, the recommended maximum melanopic EDI is 10 lx.
- The sleep environment should be as dark as possible with a recommended maximum melanopic EDI of 1 lx and 10 lx in case unavoidable activities during the nighttime require vision.

The recommendations provide highly needed additional considerations and guidance to successfully accomplish integrative lighting solutions. They are intended for healthy adults (18–55 years) with a day-active schedule, without the intention to supersede existing guidelines and regulations relating to for instance, visual function, comfort and energy consumption.

In this issue of LRT, Rea introduces and adopts an extension of the circadian stimulus (CS) model[13,14] to specify recommendations for circadian-effective lighting. Both the CS model and its extension express the amount of circadian-effective light within a light stimulus in terms of a non-SI compliant $CL_A2.0$ parameter, defined by means of the spectral irradiance and a non-linear expression that adopts several spectral sensitivity functions. The expression is derived from an early computational model for spectrally opponent circadian phototransduction[15] and has a peak sensitivity at 460 nm for short-wavelength-dominated light exposures ($b-y>0$), and at 485 nm for long-wavelength-dominated light exposures ($b-y\leqslant 0$). A fixed dose–response relationship is used to convert the $CL_A2.0$ parameter into an instantaneous 'effective magnitude of neural signals for the circadian system', that is, the CS. The CS value expresses the level of melatonin suppression that is expected to result from a nighttime light stimulus (with a particular $CL_A2.0$ value). A CS value of 0.1 or 0.3 corresponds to 10% or 30% melatonin suppression, respectively.

The CS model extension, CS_t, adds the exposure duration t to the CS model, using the law of reciprocity as a first approximation: for exposure durations between 30 minutes and up to 3 hours a lower level of circadian-effective light can be compensated by a longer exposure duration as to result in the same CS. Rea combines this CS_t model with the UL24480 Design Guideline recommendation for daytime light exposure (i.e. at least 2 hours with CS = 0.30) to yield a minimum dose of circadian-effective light CS_d of 0.43 for day-active and night-inactive building occupants. By 8 PM, the UL24480 Design Guideline recommends to use light that produces less than 10% melatonin suppression (i.e. CS ⩽ 0.10).

There are several important concerns that need reflection when using CS-based models to describe light conditions and lighting designs:

(1) The $CL_A2.0$ parameter and other CS-related measures are not SI compliant, while for international guidelines and traceable measurements in light and lighting a metrology that complies with the International System of Units (SI)[16] is essential.[17]
(2) The CS models are based on two spectral sensitivity functions that combine input from the melanopsin-based photoreceptor with rod and cone inputs. There is no scientific evidence that such a complex interplay of photoreceptors is needed to describe nocturnal melatonin suppression. An extensive body of research from a large number of independent research groups suggests that for most practically relevant circumstances, the spectral

sensitivity of melatonin suppression and phase shifting responses to light in humans can be well approximated by the spectral sensitivity of the melanopsin-based photoreceptor.[8,11,12,18–23]

(3) The fixed $CL_A2.0$–CS (dose–response) relationship as used in the CS model is primarily derived from two melatonin suppression studies for narrowband nocturnal light exposures in people with pharmacologically dilated pupils. The model has been proven to effectively describe data from a somewhat wider selection (see Rea in this LRT issue) of melatonin suppression studies with and without pupil dilator. The CS model does not discriminate between cases with or without pharmacological pupil dilation. In contrast, melanopic EDI-based recommendations and predictive models typically differentiate between cases with and without pharmacological pupil dilation, as pharmacological pupil dilation is known to reduce the thresholds for circadian responses to light.[11,12,24]

(4) The CS models have their maximum value set to 0.7 (i.e. 70% melatonin suppression), which means that they are unable to account for more than 70% melatonin suppression. A recent laboratory study[25] has found near to full (>99%) suppression of melatonin on 61 nights while exposing 55 individuals to a wide range of evening light conditions (10–2000 lx, 4100 K, for 5 hours, starting 2 hours before dim light melatonin onset). In about 80% of the tested individuals, an illuminance of 100 lx already produced a melatonin suppression of at least 75%.

(5) The CS model predictions have been verified and tested using data from a limited number of studies (see Rea in this LRT issue), while today's literature provides a much larger collection of studies with data on melatonin suppression and other circadian responses to light.[11,20,21,25] The melanopic EDI-based recommendations and predictions[11,12] have been derived and validated using a more extensive data set featuring a larger diversity and number of studies as compared to their CS-based counterparts.

In view of the above concerns, it is important to make a careful and balanced comparison between CS-based and melanopic EDI-based healthy light recommendations and predictions of nighttime light-induced melatonin suppression. A recently published generalized model used a machine learning approach and data from 29 peer-reviewed publications to predict nocturnal melatonin suppression by means of three light exposure characteristics: melanopic EDI, exposure duration and the use of a pharmacological pupil dilator (y/n). Figure 1 displays a simulation of this generalized model and compares its predictions to the corresponding CS_t model predictions. The figure clearly displays that both models predict more melatonin suppression for longer exposure durations. In contrast to the melanopic EDI-based model, the CS model cannot account for more than 70% melatonin suppression; neither does the CS model differentiate between cases with or without pharmacological pupil dilation.

In Figure 2, the CS-based daytime light recommendation from the UL Design Guideline (at least a CS of 0.3 for 2 hours during daytime, which corresponds to $CL_A2.0 = 274$ for 2 hours, and according to Rea to $CS_d = 0.43$) is converted into the corresponding photopic illuminance and melanopic EDI values for 1495 white light-emitting diode (LED) sources[28,29] with a wide range of correlated colour temperatures (CCTs).

All melanopic EDIs in Figure 2 are below the minimum of 250 lx melanopic EDI, as recommended for daytime light exposure by the expert workshop.[12] This indicates that the CS-based recommendation for healthy daytime light

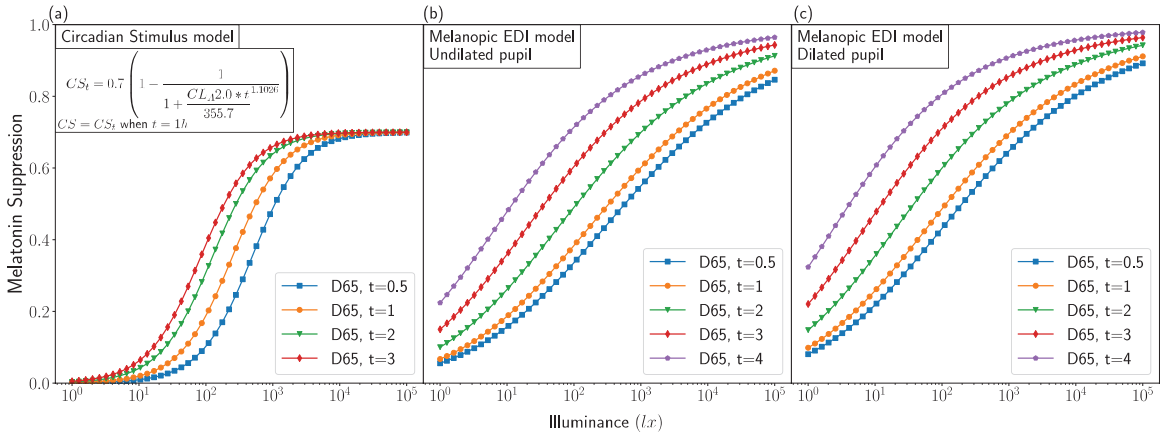

Figure 1 The % melatonin suppression (with 1 corresponding to 100%) as a function of the (photopic) illuminance of CIE standard illuminant D65 for a nocturnal light exposure with an exposure duration, *t*, of 0.5, 1, 2, 3 and 4 hours, (a) as predicted by the $CL_A2.0$-based CS_t model, here $t=4$ hours is not included since the CS_t model has only been tested for durations between 0.5 and 3 hours, (b) as predicted by the melanopic EDI-based logistic model from Giménez *et al.*[11] for a situation with and without pharmacological pupil dilation (c). For D65, the photopic illuminance equals the melanopic EDI.[9,26] The calculations were implemented using the open-source LuxPy Phyton Toolbox for Lighting and Color Science v1.9.6.[27]
CS: circadian stimulus; EDI: equivalent daylight illuminance

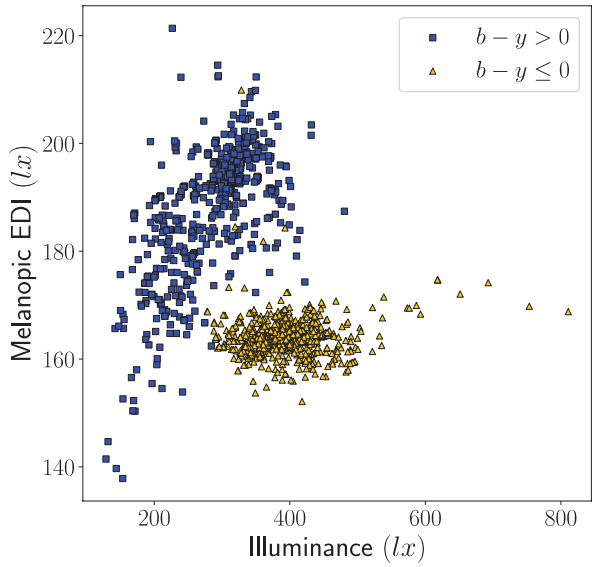

Figure 2 The photopic illuminance and melanopic EDI that corresponds to CS=0.3 (i.e. $CL_A2.0=274$) for 1495 white LED sources[28,29] with different SPDs across a wide range of CCTs. Each point in the figure has a $CL_A2.0$ of 274, and for $t=0.5$, 1, 2 and 3 hours this corresponds to a CS_t of 0.18, 0.30, 0.43 and 0.50, respectively. The blue squares denote SPDs for which $b-y>0$ and the yellow triangles denote SPDs for which $b-y\leqslant 0$. For visualization purposes, 3 out of the 1495 light sources are not included in the figure: their CCT was below 1725 K (i.e. $b-y\leqslant 0$) and although their melanopic EDI was in the normal range, their illuminance was at least twice the illuminance of the rightmost point in the figure. The calculations were implemented using the open-source LuxPy Phyton Toolbox for Lighting and Color Science v1.9.6[27]
CCTs: correlated colour temperatures; CS: circadian stimulus; EDI: equivalent daylight illuminance; LED: light-emitting diode; SPDs: spectral power distributions

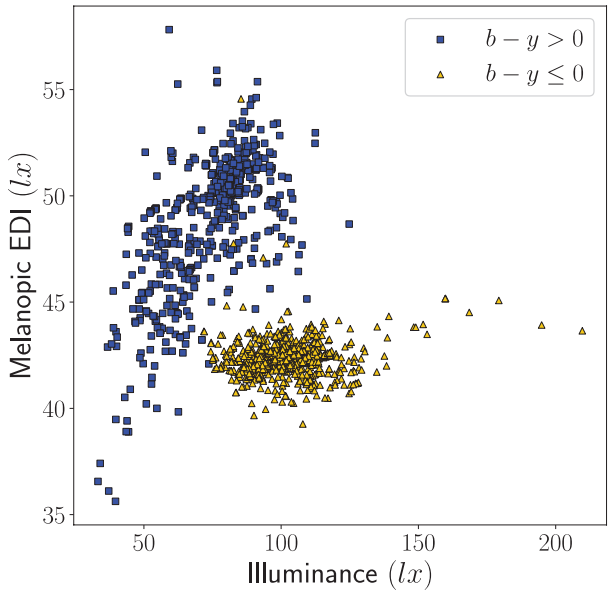

Figure 3 Comparison of the melanopic EDI and photopic illuminance that correspond to CS = 0.1 (i.e. when scaling all SPDs to $CL_A2.0 = 70$) for a large database[28,29] with SPDs from 1495 white LED sources. Each point in the figure has a $CL_A2.0$ of 70, and for $t = 0.5$, 1, 2 and 3 hours this corresponds to a CS_t of 0.05, 0.1, 0.18 and 0.25, respectively. The blue squares denote SPDs for which $b-y>0$ and the yellow triangles denote SPDs for which $b-y\leqslant 0$. For visualization purposes, 3 out of the 1495 light sources are not included in the figure: their CCT was below 1725 K (i.e. $b-y\leqslant 0$) and although their melanopic EDI was in the normal range, their illuminance was at least twice the illuminance of the rightmost point in the figure. The calculations were implemented using the open-source LuxPy Phyton Toolbox for Lighting and Color Science v1.9.6[27]
CCTs: correlated colour temperatures; CS: circadian stimulus; EDI: equivalent daylight illuminance; LED: light-emitting diode; SPDs: spectral power distributions

exposure is on the conservative side, and for all of the investigated LED sources insufficient to meet the recommendations from the international expert workshop.

In Figure 3, the CS-based recommendation for evening and nighttime light from the UL Design Guideline (a CS of maximally 0.1, which corresponds to $CL_A2.0 = 70$) is converted into the corresponding photopic illuminance and melanopic EDI for the same 1495 white LED sources as used in Figure 2.

All melanopic EDIs in Figure 3 are above the maximum melanopic EDI of 10 lx for evening light exposure (starting at least 3 hours before bedtime), as recommended by the expert workshop.[12] This indicates that the CS-based recommendation for evening and nighttime light provides less (and potentially even insufficient) protection against the sleep- and circadian rhythm-disturbing effects of evening (and nighttime) light exposures than the recommendations from the international expert workshop.

Figure 4 provides a different representation of the data shown in Figures 2 and 3. It displays the melanopic EDI and $CL_A2.0$ value per lx for each of the 1495 light sources plotted as a function of the CCT of the sources. This figure is included to provide lighting designers and practitioners with some first-order practical guidance on how to adjust CCT and illuminance as to reach a particular melanopic EDI or CS threshold value (see figure caption for more details).

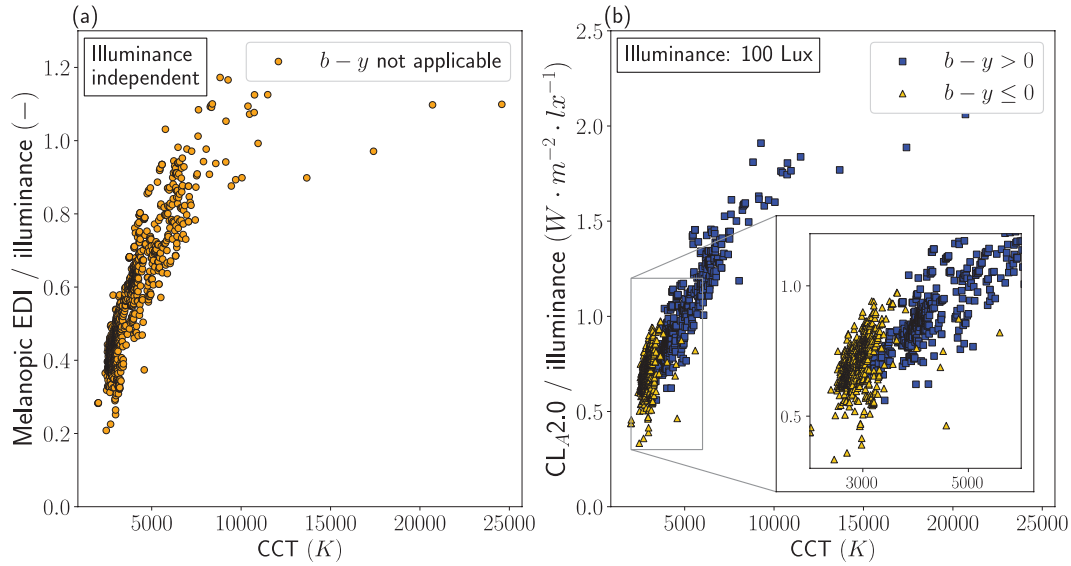

Figure 4 The illuminance-normalized melanopic EDI (a) and illuminance-normalized $CL_A2.0$ values (b) for 1495 LED sources as a function of their CCT. The *y*-axes represent the melanopic EDI and the $CL_A2.0$ value per lx of the source: 1 lx of the source produces a melanopic EDI or $CL_A2.0$ that equals the value on the *y*-axis, while 100 lx produces 100 times that value. The term melanopic daylight efficacy ratio (melanopic DER) as defined in international standard CIE S026[9] is equivalent to the illuminance-normalized melanopic EDI (= melanopic EDI/illuminance) of the light source.[26] This feature represents a dimensionless 'M/P ratio' that is a light source characteristic, quite analogously to the S/P ratio (R_{SP}) which is defined as the scotopic luminous output of a source divided by its (photopic) luminous output (see https://cie.co.at/eilvterm/17-21-113 and Schlangen and Price[26]). In contrast to the illuminance-normalized melanopic EDI, the illuminance-normalized $CL_A2.0$ (i.e. $CL_A2.0$/illuminance) of a source is not fully constant across the illuminance range. However, the deviations are of little practical relevance: at an illuminance of 1 lx, the $CL_A2.0$/illuminance has a mean, median, and largest difference (in %) from the values as plotted in the figure (which were calculated for an illuminance of 100 lx) of –0.26%, –0.14% and –0.9%, respectively. For an illuminance of 1000 lx, these differences are 2.26%, 1.26% and 7.59%, respectively, and for 2000 lx they are 4.54%, 2.56% and 14.9%. Overall, the illuminance-normalized values tend to increase with increasing CCT, yet the illlluminance-normalized values can be quite different for a given CCT (as multiple SPDs can result in the same CCT[30,31]). The calculations were implemented using the open-source LuxPy Phyton Toolbox for Lighting and Color Science v1.9.6[27]
CCTs: correlated colour temperatures; EDI: equivalent daylight illuminance; LED: light-emitting diode; SPDs: spectral power distributions

In conclusion, the standardized α-opic metrology (CIE S 026/E:2018[9]) and the melanopic EDI-based recommendations[12] provide a powerful and straightforward framework to inform light researchers, designers and other indoor professionals on light and lighting that optimally supports human health. They are (i) supported by a wide scientific consensus and evidence base, (ii) SI compliant and (iii) modular, thus enabling for future refinements while insights on the influence of other (α-opic) photoreceptors develop. The concerns and observations regarding the CS and CS_t models as put forward in this work justify a further debate on whether these models can be considered an appropriate framework to assess 'adequate circadian light exposure' throughout daytime or nighttime. In addition, the CS-based recommendations as provided in the UL24480 Design Guideline seem insufficient to secure the merits of bright days and dim nights for integrative lighting solutions.

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Reply from M Rea

Preface

At the outset, I would like to thank *Lighting Research and Technology* (*LR&T*) Editor-in-Chief Steve Fotios for providing a forum for public discussion of the Circadian Stimulus (CS) model[1–3] and the UL 24480 Design Guideline (DG).[4] I would also like to thank Luc Schlangen and his colleagues for the courage and professionalism exemplified by their submission of this communication to *LR&T* for publication. It is the first time I have had the opportunity to formally respond to direct questions about the CS model.

1. Introduction

There are two fundamental problems with the ideas expressed in the correspondence from Dr. Schlangen and colleagues, both stemming from the composition of the members and the processes that were followed by the self-appointed 'expert' panel.[5] The first problem pertains to science, the second pertains to application. With regard to the science, in brief, there is no way that qualified experts could reasonably argue that a single photoreceptor (i.e. the ipRGC) is responsible for circadian phototransduction. As is well established from many lines of enquiry,[1–3,6–9] the neural signals reaching the biological clock in the suprachiasmatic nuclei (SCN) reflect the combined input from not just *all* photoreceptors, but, importantly, the connecting neurons more distal to the ipRGC. This is a simple fact, simplistically dismissed by the Brown group when they say that melanopic equivalent daylight illuminance (mEDI) is all that is needed to be 'practically relevant'.

The second problem is, indeed, the 'practically relevant' recommendations offered by the Brown group for architectural applications and used by Dr. Schlangen and colleagues in their correspondence. The application recommendations were not informed by individuals who have experience in commerce, engineering, energy efficiency, architecture or even different branches of science. The Brown group recommendations are quite unlike those of the UL 24480 DG, which they fail to cite, and which explicitly followed the ANSI Essential Requirements with respect to due process, openness, lack of dominance, balance, public comment and consensus vote. Consequently, the Brown group's daytime recommendations, if followed, would unnecessarily waste electric energy devoted to lighting and the nighttime recommendations would, if followed, unnecessarily have a negative impact on the visual requirements for safe and pleasant lighting in residences. If the Brown group had followed the ANSI Essential Requirements by incorporating the views of application experts, these application flaws might have been avoided.

I will address the correspondence from Dr. Schlangen and colleagues within these two domains, science and application, at several levels.

2. Science

By far, the biggest issue with the correspondence by Dr. Schlangen and colleagues is that they, and presumably others, do not seem to grasp what the CS model actually is and what it is not. The CS model is a mathematical representation of the circadian phototransduction mechanisms in the retina. It is *not* a model of nocturnal melatonin suppression; thus, it is intended to be useful in characterizing circadian-effective light, both night and day. This important distinction has recently been discussed.[3] Nocturnal melatonin suppression is the convenient outcome measure used to psychophysically infer the characteristics of the retinal mechanisms providing neural signals to the SCN. We have published much on the justification for using nocturnal melatonin suppression as the outcome measure and, to limit my comments to the correspondence by Dr. Schlangen and colleagues, I will simply redirect

the reader to the paper being discussed here (see also Moore[10]). Quite importantly, and this point should not be overlooked or trivialized, the inferred model of circadian phototransduction within the retina is not based on melatonin suppression data alone; rather, the model is also consistent with the wealth of information in the literature describing the neuroanatomy and neurophysiology of the retina.[2] I direct the reader to the extraordinary body of work led by Helga Kolb on this important area of science.[11–13]

Hopefully, the reader may appreciate the close analogy between the development of the circadian spectral sensitivity function, CL_A, used in the CS model, and the development of the photopic luminous efficiency function ($V(\lambda)$) in 1924. The photopic luminous efficiency function was intended and was subsequently described as the human eye's spectral sensitivity to electromagnetic radiation.[14] It was derived largely from experiments employing flicker photometry, again described elsewhere,[15] but it was never intended to simply represent the spectral sensitivity of the human visual system to flickering lights. It was developed to represent our overall spectral sensitivity to electromagnetic radiation with the specific aim of supporting lighting manufacturers around the world by having a common definition and metric for *light*.[14] Flicker photometry was chosen without any regard for retinal neuroanatomy or neurophysiology because it was simply the most precise psychophysical method at the time for, presumably, determining our spectral sensitivity function to electromagnetic radiation. We now know, through a great deal of research conducted since 1924, that $V(\lambda)$ does *not* characterize our overall spectral sensitivity to electromagnetic radiation. We now know that $V(\lambda)$ reflects the combined spectral sensitivities of the L- and M-cones as they feed the magnocellular (M) (fast responding/low spatial resolution) channel of the retina.[16]

Although not useful as a characterization of our overall spectral sensitivity to electromagnetic radiation, $V(\lambda)$ was subsequently found useful for characterizing the spectral sensitivity of visual performance and on-axis detection.[16] The progress towards our current understanding of $V(\lambda)$ and of CL_A has only come through converging studies of neuroanatomy, neurophysiology and hypothesis-driven psychophysics. This point is not trivial but is not even part of the correspondence from Dr. Schlangen and colleagues, nor from the Brown group. Without that convergence researchers would, as they did in 1924 and again here with respect to circadian-effective light, fail to understand what the spectral sensitivity data mean and where they might be appropriately employed. More perniciously perhaps, without an intellectual commitment by scientists for convergence, they will fail to accept a complete understanding of the biophysics of the retina and consequently provide a shaky foundation for application.

So, in sum, just as $V(\lambda)$ was never intended to be a model of flicker spectral sensitivity, CL_A was never intended to be a model of melatonin suppression spectral sensitivity. Flicker photometry and nocturnal melatonin suppression were both convenient psychophysical outcome measures for inferring the spectral sensitivity of a neural channel in the retina. Quite unlike the development of $V(\lambda)$, however, the development to CL_A was always grounded in retinal neurophysiology and neuroanatomy, thereby providing a more complete understanding of the underlying retinal mechanisms and a firmer foundation for application.

It is particularly telling that Dr. Schlangen and colleagues and the Brown group do not attempt to address retinal neurophysiology and neuroanatomy to support their recommendations. They take an unwise shortcut to conclude that one only needs to consider ipRGCs to be 'practically relevant' for predicting circadian responses to light exposure on the retina. I suspect that this superficial appreciation of circadian phototransduction mechanisms in the retina leads them to a form of

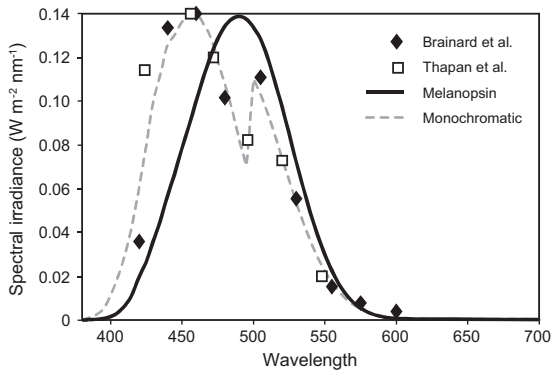

Figure 1 Spectral sensitivity of the circadian phototransduction mechanisms in the retina affecting the SCN, as measured by nocturnal melatonin suppression, to narrow-band (monochromatic) photic stimulation. The solid line represents the relative luminous efficiency of melanopsin while the dashed line represents the estimated spectral sensitivity of the circadian phototransduction mechanisms to narrow-band lights based upon CL_A

intellectual myopia. I have published several papers on the inadequacy of melanopsin alone, the photopigment in the ipRGCs, to characterize the spectral sensitivity of the neural channel affecting the SCN.[15,17–19] Its inadequacy is obvious to anyone with an open mind, particularly in comparison to CL_A, which, again, is informed by retinal neurophysiology and neuroanatomy (Figure 1).

Without going into a detailed discussion of retinal neurophysiology and neuroanatomy which has been published elsewhere,[2] an understanding of the retinal mechanisms made it possible for us to mathematically predict several phenomena that are completely unaddressed by Dr. Schlangen and colleagues and by the Brown group. Two important phenomena are (a) the higher threshold for circadian system stimulation for diurnal humans than for nocturnal rodents and (b) the non-linear, sub-additive response by the human circadian system to combined wavelengths. Again, it is telling that Dr. Schlangen and colleagues and the Brown group never even mention these important phenomena.

As an aside, it is important to also understand one major difference between the intended use of $V(\lambda)$ and that of CL_A. The former was and is aimed at supporting international commerce, so it is essentially irrelevant for manufacturers whether $V(\lambda)$ has anything to do with neurophysiology and neuroanatomy. Precision of measurement is all that matters for industry. In contrast, CL_A was never intended to be a metric for commerce. Rather, it was designed to be a metric that could be used by illuminating engineers to quantify a benefit (circadian entrainment) and reliably deliver that benefit to occupants of architectural spaces.[4,19,20] (In the present context, the term 'circadian entrainment' refers to the 24-hour pattern of behaviour where an individual is active every day and asleep every night. Different degrees of circadian entrainment are exhibited when the timing or duration of sleep varies across 24-hour periods). In this regard, the α-opic efficiency functions and the International System of Units (SI) referred to by Dr. Schlangen and colleagues need further comment. Without question, it is essential for commerce to have standardized units of measurement, including photometry, but there is a sharp distinction between physical units – like the second, the meter and the kilogram – and a biophysical unit like the candela. Again, *all of these SI units were developed to support international commerce*, and the biophysical candela has served the lighting industry very well. However, the candela and derivative units, like illuminance and luminance, are only convenient measures of the photic stimulus, but scientists should never assume that candela-based quantities accurately characterize the photic stimulus in their various experiments.

To understand the biophysics of visual and non-visual phototransduction mechanisms, one needs to rely upon strictly physical characterizations of the stimulus, such as irradiance and radiance, derived from the basic quantities, not biophysical constructs such as illuminance and luminance. So, the candela and the α-opic units,

as SI units, are of no particular value for scientific enquiry. Scientists should rely upon the converging published literature previously discussed to understand natural phenomena surrounding retinal phototransduction mechanisms and they should not be constrained to use biophysical units that may or may not have relevance to an understanding of retinal mechanisms. Indeed, a deep and broad legacy of understanding surrounding the biophysics of the retina has progressed very nicely over the last century without the use of 'commercialized' biophysical units. In short, science and commerce should be conceptually segregated.

Stemming from the basic misunderstanding that CS is a model of circadian phototransduction, Dr. Schlangen and colleagues do not appreciate that our studies measuring nocturnal melatonin suppression for different durations of exposure to light (*t*) and for different distributions of light across the retina (*f*) were conducted to validate the model of circadian phototransduction. We hypothesized that if the CS formulation, including CL_A, was correct as a general model of circadian phototransduction, then the retinal mechanisms should not be differentially affected by different exposure durations and by different distributions across the retina. Obviously, the absolute amount of melatonin suppression will be different for different durations and distributions, but, if CS is a general model of circadian phototransduction, the mathematical representation of the phototransduction mechanisms should not be affected by how long those mechanisms are exposed to light or to what spatial extent those mechanisms are distributed across the retina. Importantly, our proposed validation exercise could only have worked if the relationship between the neural signal reaching the SCN and the outcome measure, nocturnal melatonin suppression, did not change. We certainly did not know that this would be true before we began the experiments (this is why a priori hypothesis testing is so important), but, in fact, we found this to be true over a limited range, 'more or less' as the title of the paper being discussed states.

So, mathematically, the terms *t* and *f* are independent of the modelled phototransduction mechanisms, thereby helping to validate the CS model. Significantly, we did not have to do post-hoc, multiple free-parameter curve fitting as some have employed (e.g. Brown[21]) to account for differences in exposure duration and distribution. In other words, since duration and amount (for a given spectrum) are 'more or less' independent, the assumption of reciprocity can be a practical design strategy for supporting circadian entrainment. As articulated in the paper being discussed, however, there must be temporal limits (time and duration of exposure) to this reciprocity, but, importantly, there is no reason to believe that the circadian phototransduction mechanisms change their biophysical relationship within our articulated ranges of durations and amounts. Of course, reciprocity may not hold under all circumstances. For example, the sensitivity of the retina may vary with circadian phase[22] but, to date, there is no evidence that reciprocity cannot be used 'more or less', within the stated limits, as a design strategy for delivering circadian-effective lighting in architectural spaces. Here it is worth making the essential point again that CS is a model of circadian phototransduction, not melatonin suppression. Just because melatonin suppression changes with duration (or time of day) does not necessarily mean that the retinal phototransduction mechanisms change with duration (or time of day), as some have inferred,[23] and which we have discussed.[24] Psychophysical experiments need to be performed to differentiate changes in spectral sensitivity and the operating characteristics of the phototransduction mechanisms from post-retinal effects like habituation or sensitization.

As another example of the misunderstanding of the CS model, inferences drawn about the spectral sensitivity of the phototransduction mechanisms, CL_A, and the operating characteristic, CS, do not

depend upon the absolute values of melatonin suppression. As long as duration, distribution, spectrum and timing are not confounded, only the relative changes in nocturnal melatonin suppression are important. For example, it is possible to combine the Jefferson study[25] using a 90-minute exposure duration with Surrey study,[26] which used a 30-minute exposure duration (both of which are within the duration limits articulated in the paper being discussed), to determine the spectral sensitivity of the phototransduction mechanisms to narrow band spectra if – and only if – the two studies use a constant criterion method (e.g. 35% suppression) for assessing the relative sensitivity to different wavelengths.[1] This is exactly what the developers of $V(\lambda)$ did in 1924 and what we did with the Jefferson and Surrey data (see Figure 1).[1] Yes, there was more nocturnal melatonin suppression in the Jefferson study because longer durations were used than in the Surrey study, but this difference is irrelevant for characterizing the spectral sensitivity of the phototransduction mechanisms *as long as* the operating characteristic of the phototransduction mechanisms do not change with duration, which they do not over this range of durations, as we later showed.[3,15]

As a side note, once the full range of operation by the phototransduction mechanisms in the retina is determined, picking the half-saturation response to different wavelengths minimizes the need to accurately model the operating characteristic; no matter what form of the equation representing all of the data takes, any reasonable monotonic function fitting the fixed-wavelength/variable-amount data can be used to reliably estimate the half-saturation point.[27,28] To again underscore the difference between a model of circadian phototransduction and a model of melatonin suppression, the former is completely independent of the absolute value of nocturnal melatonin suppression as long as there are no confounds with factors that can affect suppression. This also means that the operating characteristics of circadian phototransduction retinal mechanisms do not change with pupil dilation or constriction, as suggested by Dr. Schlangen and colleagues, even though melatonin suppression will differ because the retina is exposed to different light levels. The CS model takes into account spectrally weighted *retinal irradiance*, not simply irradiance at the cornea. From a practical perspective, however, where high levels of spectrally weighted irradiance at the eyes are needed to reach the criterion of CS = 0.3 or of mEDI = 250, any changes to the already constricted pupils with changes in 'white' light spectrum will be quite small, less than 10%. Furthermore, these small changes would be even smaller for older people who already have mitotic pupils.

3. Application

Dr. Schlangen and colleagues argue that light exposures of CS = 0.3 for 2 hours in the UL 24480 DG are lower than those provided by the Brown group of mEDI of 250 throughout the day. Indeed, these two light exposure recommendations are *very* different and would be associated with *very* different lighting energy requirements. The foundation for the Brown group light exposure recommendation is not documented, although their recommendation will undoubtedly support circadian entrainment. It is important to remember, however, that circadian entrainment is only one important lighting design criterion. Energy requirements are also important, and the authors of UL 24480 DG were keenly aware of this lighting design criterion. Therefore, they were looking to set a *minimum* light exposure that would support circadian entrainment among the general population without wasting lighting energy. In that regard, it is important to understand that recommendations for circadian entrainment are about *dose*, so *both* the amount of light exposure and the duration of light exposure are important. And of course, for lighting energy use, both the watts needed to power the lighting system and the duration of its operation are important.

A wide variety of peer-reviewed field studies, none of which were acknowledged by Dr. Schlangen and colleagues or were cited in the document published by the Brown group, support the conclusion that CS > 0.3 during the day promotes better sleep efficiency, shorter sleep latency and, in some cases, lower depression compared to control groups with CS < 0.15.[29–34] So, in terms of amount, there is ample empirical evidence from these field studies showing that one does not need light levels as high as those proposed by the Brown group to support circadian entrainment and thus, better sleep outcomes. The results of these published field studies are, of course, based upon people living their normal lives, being awake during the day and asleep at home during the night. Therefore, the field study literature is silent with respect to the minimum duration of light exposure during the daytime that would be needed to support circadian entrainment. The authors of UL 24480 DG had to rely on other sources of information to estimate the minimum duration of light exposure needed during the day for circadian entrainment. Wittmann *et al*.[35] have utilized self-reported times of mid-sleep at night as an outcome measure for what they term 'social jet lag' which, in simple terms, is a measure of circadian misalignment or the opposite of circadian entrainment. Those people who have consistent sleep–wake patterns on both workdays and free days exhibit minimum 'social jet lag' and, by extension, are better entrained. Roenneberg and Merrow[36] showed that mid-sleep during workdays was later and more variable among those people who did not receive several hours of natural daylight. Importantly for the authors of UL 24480 DG, there was no evidence from Roenneberg and Merrow that mid-sleep for those people receiving greater than 5 hours of daylight was different from those people receiving only 2 hours of daylight. Therefore, in the interest of minimizing wasted electric lighting energy, the authors of UL 24480 DG recommended a CS > 0.3 (amount) for a minimum of 2 hours (duration) to support circadian entrainment, and thus better sleep. To my knowledge, there is no empirical evidence that would contradict this light dose recommendation for supporting circadian entrainment. Certainly, neither Dr. Schlangen and colleagues nor the Brown group offer any evidence to the contrary. Compared to the amount and duration of light exposure recommended by UL 24480 DG, the undocumented recommendation from the Brown group would require approximately 9× the electric lighting energy because the amount of light exposure would be greater, and the duration of light exposure would be much longer.

Admittedly, the certainty surrounding any discussion of evening light exposure on circadian disruption is less than it is for daytime light exposure. For example, the impact of evening light exposure will depend upon previous light exposure.[37–39] In general, however, everyone agrees that bright days should be followed by dim evenings for circadian entrainment. Dr. Schlangen and colleagues correctly point out that the suggested minimum of CS < 0.1 in the UL 24480 DG is a more liberal definition of 'dim' than the panel's recommendation of 10 mEDI. It is not at all clear where the 10 mEDI came from in the original document by the Brown group, but the rationale for CS < 0.1 during the evening was three-fold. First, UL 24480 DG is primarily concerned with daytime light exposure. Still, it is true that CS < 0.1 was included in the UL 24480 DG, although, again, the certainty surrounding that recommendation is less. Second, the recommended value of CS < 0.1 for the evening was driven mainly from laboratory findings of melatonin suppression. At these low light levels, melatonin suppression becomes highly variable.[40] In other words, it is difficult to obtain reliable measurements of melatonin suppression at levels below CS = 0.1, even for durations as long as 1 hour. Although this uncertainty probably is associated with the response of the pineal to dim

light and not to the retinal circadian phototransduction mechanisms, it is not possible at this time to know for certain. Third, and most importantly, the authors of UL 24480 DG did not want to contradict current lighting recommendations for residences, where most evening light exposures occur.

People not only sleep at home, but they also eat meals, watch television, read books and interact with one another. In North America, there are long-standing illuminance recommendations, in photopic lux, provided by the Illuminating Engineering Society (IES) for residential areas and visual tasks.[41] They include illuminance level recommendations on a horizontal (task) plane and on a vertical (at the eye) plane. These recommended light levels will typically come from a 'warm appearing light source such as incandescent' (p. 5) in the evening. So, for comparison, an incandescent source producing 10 mEDI at the corneas would produce 20 lx at the corneas and for a CS = 0.1, that same light source would produce 80 lx at the cornea. If one considers the 84 illuminance recommendations provided by the IES for different areas and activities performed in residences, 20 (24%) would not meet either the mEDI or the CS limits. However, many of these tasks typically would not be performed in the evening (e.g. grooming, 400 lx) nor for a very long time (e.g. searching through drawers, 100 lx). Still, it is possible that individuals might very well do arts and crafts (300 lx) or read music (200 lx) for an extended period of time in the evening at home. For these tasks, no one really knows whether those illuminated tasks induce circadian misalignment or not, so, in the future, it is important to conduct carefully controlled field research to more fully understand how the circadian system might be affected when these tasks are typically performed in the evening.

Among the 84 illuminance recommendations, 21 (25%) would be acceptably below the recommended limits of light exposure from both the Brown group and the UL 24480 DG recommendations. This leaves 63 tasks (75%) of the light levels recommended by the IES as too high for the Brown group's recommendation of mEDI < 10. In contrast, the UL 24480 DG is more consistent with the long-standing IES recommendations than with the Brown group's recommendation. Only 24% of the IES residential lighting recommendations would exceed the UL 24480 DG recommendation of CS < 0.1. But, honestly, no one really knows how the circadian system would be affected by these illuminated tasks performed in the evening at home. Again, well-controlled field studies are called for. But, given the measurement uncertainty at low light levels in melatonin suppression, our most reliable biomarker for stimulation of the circadian system, a large amount of data would have to be collected to obtain a reliable answer to the question.[40] Absent that data, however, I would argue that it is worse to have inconsistency with recommendations from other bodies like the IES than it is to make recommendations like those from the Brown group without empirical foundation and without input from a balanced committee as specified in the ANSI Essential Requirements.

Again, I very much appreciate the opportunity to respond to the communication by Dr. Schlangen and colleagues.

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