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Recommendations for healthy daytime, evening, and night-time indoor light exposure

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ABSTRACT

Ocular light exposure has important influences on human health and well-being through modulation of circadian rhythms and sleep, as well as neuroendocrine and cognitive functions. Current patterns of light exposure do not optimally engage these actions for many individuals, but advances in our understanding of the underpinning mechanisms and emerging lighting technologies now present opportunities to adjust lighting to promote optimal physical and mental health and performance. A newly developed, SI-compliant standard provides a way of quantifying the influence of light on the intrinsically photosensitive, melanopsin-expressing, retinal neurons that mediate these effects. The present report provides recommendations for lighting, based on an expert-scientific consensus and expressed according to this new measurement standard. These recommendations are supported by a comprehensive analysis of the sensitivity of human 'non-visual' responses to ocular light, are centred on an easily measured quantity (melanopic equivalent daylight (D65) illuminance), and provide a straightforward framework to inform lighting design and practice.

THE NEED FOR GUIDANCE

Besides supporting visual perception, ocular light exposure influences many aspects of human physiology and behaviour, including circadian rhythms, alertness and sleep, mood, neuroendocrine and cognitive function[1-3]. This array of retinally-driven responses to light (collectively termed here: 'non-visual' for brevity) are important determinants of health, well-being and performance, and some are already clinically relevant, as evidenced by current light therapy for circadian rhythm sleep disorders and various forms of depression[4,5]. Industrialisation and urbanisation have progressively and dramatically altered individuals' light exposures, resulting in less light, including natural light, during the daytime and less darkness during the night, due to spending more time indoors where electrical lighting provides the dominant source of illumination. Substantial evidence shows that such altered light exposure patterns have negative impacts on health and productivity[6-9]. Therefore, there is an urgent need for evidence-led recommendations to help inform the design and application of light emission technologies and human exposures.

To date, a key challenge to optimizing light exposure for promoting human health, well-being and performance has been the lack of an accepted scientific framework upon which to quantify the propensity for light to elicit the relevant responses and from which to base recommendations for lighting design and practice. Fortunately, as a result of several decades of scientific advances, research-based recommendations are now possible.

Building on initial observations that non-visual responses to ocular light can persist even in people who are totally visually blind[10-12], convergent evidence from studies of humans and animals has shown that such physiological responses originate via a specialised class of retinal neurons, the intrinsically photosensitive retinal ganglion cells (ipRGCs)[13-21]. The light-sensing photopigment within the ipRGCs is melanopsin which, in humans, is maximally sensitive to photons in a distinct portion of the visible spectrum (λ_{max} ≈ 480 nm prior to accounting for filtering through the lens and ocular media) to the cone photopigments[18,20,22]. As a result, the established photometric quantities used to describe brightness and luminous sensation as perceived by humans do not adequately reflect the spectral sensitivity of any melanopsin-dependent responses to light. Rather, measures such as photopic (il)luminance, which primarily reflect the spectral sensitivity of long- and medium-wavelength sensitive cones, place substantially greater weight on longer wavelengths than those to which

melanopsin is most sensitive, and are therefore inappropriate to quantify light with respect to non-visual responses (Figure 1A).

While the potential value of a melanopsin-based photometric quantity has been recognised for some time, there has also been uncertainty as to whether this provides a sufficiently detailed model of the spectral sensitivity of human non-visual responses to ocular light[2]. Hence, while the spectral sensitivity of physiological responses to light in visually blind people and animals matches that expected for melanopsin[15,18,20,23], in the fully intact retina, ipRGCs can also receive signals originating from rods and/or cones[21]. Moreover, available data indicate that the relative contributions of melanopsin and rod/cone photoreception to non-visual ocular light responses, and consequently their apparent sensitivity, may vary as a function of exposure duration, light intensity, and perhaps time of day and/or prior light exposure[2,20,24-27].

As an initial response to the absence of a suitable metric for quantifying ipRGC-dependent ocular light responses, in 2013, an expert working group proposed a system that weighted irradiance according to the effective *in vivo* spectral sensitivity of the five known human retinal opsin proteins (melanopsin, rhodopsin, S-, M- and L-cone opsin)[2]. This framework has now been formalised as an SI-compliant system of metrology (Commission Internationale de l'Eclairage; CIE S 026)[28], where the photopic properties (e.g. illuminance) of standard daylight (D65) that match the effective rates of photon capture for each opsin are reported as α-opic equivalent daylight illuminance (α-opic EDI, Figure 1B). Moreover, as originally envisaged[2], the adoption of such approaches has facilitated a number of large scale retrospective evaluations of historical data[29-33] and informed new hypothesis-driven investigations[34-37] on the photoreceptive physiology for circadian, neuroendocrine and neurobehavioral responses in humans.

In total, the evidence from such studies[29-37] supports the view that, under most practically relevant situations (extended exposures to polychromatic light in the absence of pharmacological pupil dilation), light-sensitivity of human physiological responses can be reliably approximated by the α-opic irradiance for melanopsin or the corresponding EDI (melanopic EDI). Moreover, based on the consistency of melanopic irradiance-response relationships across studies[32], it is now possible to define realistic, evidence-based recommendations for light exposures that target non-visual responses. Therefore, there now exists an easily measured and internationally accepted SI-compliant system of metrology to inform lighting design and associated policy.

Here we describe expert consensus-based recommendations for daytime, evening and night-time light exposure and the scientific evidence supporting these, followed by considerations of their applicability and any caveats associated with the recommendations as they stand.

EXPERT CONSENSUS-BASED RECOMMENDATIONS

The 2nd International Workshop on Circadian and Neurophysiological Photometry in 2019 brought together experts in lighting, neurophysiological photometry and sleep and circadian research (all authors of this manuscript). The workshop was chaired by Brown and Wright who provided workshop participants with goals and key questions to address prior to a structured face-to-face meeting. The primary focus of the meeting was to develop expert consensus recommendations for healthy daytime and evening/night-time light environments tentatively based on the new SI-compliant measurement system (CIE S 026:2018). Initial questions for review and discussion were:

1. What range of melanopic EDI can be reasonably considered to provide minimal and maximal impacts on non-visual ocular light responses in humans?

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2. Do signals from rods and/or cones also play a major role and, if so, what relevant guideline levels could be recommended to account for such actions?
3. Do the answers to (1) and/or (2) vary across different non-visual forming responses (e.g. circadian entrainment/resetting, sleep/arousal, effects on hormone secretion, mood) and, if so, what is the most appropriate general recommendation that can be provided?

Participants were also asked to consider if recommended light exposures would vary depending on which specific biological effects one is trying to achieve and/or on the target population (e.g. shift workers, specific clinical applications, etc.). In the face-to-face meeting, the morning of the first day was devoted to detailed presentations and discussion of the relevant scientific literature and the afternoon was devoted to breakout sessions for discussion of questions 1-3 noted above. The second day was devoted to further discussion and voting to determine the expert consensus recommendations via an iterative process. Following the establishment of the expert consensus recommendations, a writing plan was formulated to produce the current paper that provides scientific evidence for the recommendations. The recommendations, described below, are intended to provide realistic targets that will result in appropriate non-visual responses to ocular light exposure in humans.

Daytime light recommendations for indoor environments

Throughout the daytime, the recommended minimum melanopic EDI is 250 lx at the eye measured in the vertical plane at ~ 1.2 m height (i.e., vertical illuminance at eye level when seated). If available, daylight should be used in the first instance to meet these levels. If additional electrical lighting is required, the polychromatic white light should ideally have a spectrum that, like natural daylight, is enriched in shorter wavelengths close to the peak of the melanopic action spectrum (Fig 1A).

Evening light recommendations for residential and other indoor environments

During the evening, starting at least three hours before bedtime, the recommended maximum melanopic EDI is 10 lux measured at the eye in the vertical plane ~ 1.2 m height. To help achieve this, where possible, the white light should have a spectrum depleted in short wavelengths close to the peak of the melanopic action spectrum.

Night-time light recommendations for the sleep environment

The sleep environment should be as dark as possible. The recommended maximum ambient melanopic EDI is 1 lux measured at the eye.

For unavoidable activities where vision is required during the nighttime, the recommended maximum melanopic EDI is 10 lux measured at the eye in the vertical plane at ~ 1.2 m height.

Additional considerations

i. Exposure to a stable and regular daily light-dark cycle is also likely to reinforce good alignment of circadian rhythms, which may further benefit sleep, cognition and health. These recommendations should therefore be applied at the same time each day, so far as possible.

ii. These recommendations are not intended to supersede existing guidelines relating to visual function and safety. The non-visual ocular light responses covered here should be an additional level of consideration provided that relevant visual standards can still be met.

iii. These recommendations are intended to apply to adults with regular daytime schedules. Special considerations may apply to specific populations (e.g. children, the elderly, shift workers) as discussed later in this publication.

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SCIENTIFIC RATIONALE

Evidence from laboratory studies

The rationale for basing these recommendations upon melanopic EDI is provided by a comprehensive analysis of data aggregated from controlled laboratory studies that have evaluated the two best understood neuroendocrine and circadian light responses in humans: acute suppression of nocturnal pineal melatonin production and circadian phase resetting by evening or nighttime light exposure[30-33]. Those data indicate that, for a wide range of monochromatic, narrowband and broadband light sources and exposure durations, such ocular light responses are better predicted by melanopic irradiance than by photopic illuminance or other previously proposed metrics. Additional contributions from photoreceptors other than melanopsin are expected based on known ipRGC biology[2,21] and evidence for such contributions has been observed under certain circumstances[24,38]. Importantly, however, the sum of empirical human data suggest that any such influences are sufficiently limited that, under most practically-relevant circumstances, the spectral sensitivity of non-visual responses to ocular light can be well-approximated by melanopic EDI.

The clearest evidence for contributions from photoreceptors other than melanopsin has so far come from evaluations of melatonin suppression in short (<1 h) time windows following exposures to monochromatic light in participants with dilated pupils (to remove indirect effects of pupil constriction on apparent sensitivity). While data from two such studies are compatible with the possibilities that S-cones[38] or the photopic system[24] may contribute alongside melanopsin, a large body of data with and without use of pupil dilation indicates that for exposures of an hour or more, melatonin suppression can be reliably predicted by melanopic EDI[31,32,39,40]. This conclusion is further strengthened by findings from recent studies that have employed photoreceptor isolating stimuli to confirm that melanopsin-selective modulations in irradiance modulate melatonin production[34,35] but failed to find any effect of large variations in irradiance selectively targeting S-cones[36]. Further evidence consistent with a dominant role for melanopsin comes from earlier observations showing that totally visually blind humans (where remaining light responses match the spectral sensitivity expected for melanopsin)[18,20] can display near-full melatonin suppression[10,12,18], as do individuals with colour-vision deficiencies[41].

In line with the data discussed above, totally visually blind subjects can also display circadian phase resetting responses to bright white light of comparable magnitude to sighted individuals [11]. Findings from one study in sighted individuals with pharmacologically dilated pupils are suggestive of cone contributions to circadian phase-resetting following long (6.5 h) exposures to dim monochromatic light[24]. However, an equivalent effect is not readily apparent across data from studies performed on participants with undilated pupils[32,42,43]. Thus, laboratory data collected under conditions that are more relevant to the real-world, where pupils are freely light responsive, indicates that the influence of cones is sufficiently small that melanopic irradiance can provide a reliable approximation of the spectral sensitivity of circadian phase resetting.

By contrast to the circadian and neuroendocrine responses discussed above, other relevant effects of light that are of importance but mechanistically less well understood, such as acute light effects on alertness, have not yet received the same degree of analytic and parametric study. A comprehensive meta-analysis suggests, however, that the self-reported alerting responses to white light are observable within a similar range of light intensities to those associated with effects on the circadian system irrespective of time of day[3]. While that analysis did not reach definitive conclusions on the spectral sensitivity of alerting responses, the most informative studies included there[44-49] and other relevant studies and meta-analyses[30,32,33,49,50]

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indicate that alerting effects of light are better predicted by melanopic irradiance than other available metrics. The published irradiance response data for alerting responses to broadband white light[51] also closely matches the relationship between melanopic EDI and circadian-related responses determined from studies that did not employ pupil dilation[32,52,53] (Fig. 2). Moreover, findings from recent studies provide evidence that selectively increasing melanopic irradiance within this range, in the absence of changes in either illuminance or colour, can promote alertness during both day[37] and evening[34].These data do not exclude the possibility that cone signals might exert a greater influence over acute alerting responses to light than is apparent for circadian and neuroendocrine effects. Nonetheless, the bulk of available evidence supports the view that melanopic EDI is the best currently available predictor of alerting responses to light and is relevant for both day and evening/nighttime scenarios.

In sum, most of the available laboratory data suggest that melanopic EDI provides a reliable index that, in most commonly encountered scenarios, provides a good approximation of the apparent spectral sensitivity of human circadian and acute non-visual responses to ocular light. In particular, for the extended exposures to polychromatic light that are of most relevance to the real world, existing evidence indicates that any additional contributions from cones (or rods; whose spectral sensitivity is relatively close to melanopsin) do not compromise the predictive value of melanopic EDI.

As befitting a system evolved to optimise physiology and behaviour in anticipation of day-night transitions driven by the Earth's rotation relative to the sun, the operating range of human non-visual ocular light responses span the range of light intensities typically encountered between civil twilight and sunrise/sunset (i.e. melanopic EDI of ~1-1000 lx; Fig. 2). The recommendations indicated above are therefore intended to ensure that the sleeping environment is kept at a limit below which any appreciable non-visual responses are elicited, and to minimise negative effects of the pre-sleep light environment[54]. Similarly, recommendations for daytime and evening light exposure are intended, so far as practically possible, to respectively maximize and minimize any associated effects on sleep, alertness and the circadian system.

Evidence from real-world settings

While our current understanding of the spectral sensitivity and dynamic range of circadian, neuroendocrine and neurobehavioral light responses in humans is most directly informed by laboratory studies, our recommendations are also supported by field evaluations of the impact of environmental lighting.

Access to electric lighting is associated with reduced daytime and increased night-time light exposure and altered sleep timing[55-58], with many individuals in modern society routinely experiencing melanopic EDI <250 lx during the day, especially those with delayed sleep schedules[59,60]. Accordingly, there have been a number of real-world studies implementing daytime high melanopic lighting interventions in workplaces, schools, and care homes that provide practical corroboration for the recommendation outlined above[61].

In offices, increasing the melanopic output of architectural lighting (~2-fold) via short wavelength-enriched (17000 K) lamps had beneficial effects on self-reported alertness, performance, mood and sleep quality[62,63]. Similarly, enhancing daytime melanopic exposure by increased access to natural daylight in the workplace improved sleep and cognitive performance in office workers[64]. In these studies[62-64], the average melanopic EDI in the control working environment was <150 lx (standard 3000-4000 K fluorescent lighting; Figure 3A), with the active conditions increasing melanopic EDI to ~170-290 lx. Hence modest and readily

achievable adjustments to increase light exposure can be associated with measurable benefits, without any observable detrimental effects.

In schools, findings from a series of studies employing fluorescent lighting with various intensities and spectra indicate that settings with a higher melanopic output (melanopic EDI >500 lx) can improve measures of concentration and reading comprehension compared to current standard lighting (typically providing melanopic EDI <200 lx)[65-68]. Similar benefits of short wavelength-enriched (17000 K) vs. standard 4000 K fluorescent light on reducing sleepiness have also been shown in college-aged students during afternoon lectures[69]. Further, building on seminal work showing the benefits of increased daytime light levels for the elderly[70], several clinical trials have shown the benefits of enhanced melanopic light exposure during daytime hours on care home residents[71-73]. In these studies, compared to control conditions (typical daytime melanopic EDI <150 lx), implementation of higher melanopic, short-wavelength enriched, polychromatic lighting (5500-17000K) led to a range of improvements including reduced depression, agitation and anxiety, better daytime activity and, in some studies, improved sleep quality.

Collectively, increasing melanopic light exposure during the day in line with our recommendations has been shown to benefit alertness, performance and sleep in a wide range of real-world settings, even in the presence of daylight or stimulants such as caffeine. Also of importance, at this time, there is minimal evidence for negative effects of increased daytime melanopic light exposures. One care home study[73], where the brightest daytime light intervention was examined (melanopic EDI ~900 lx; 17000K), reported a reduction in sleep efficiency and quality when compared to standard 4000k lighting (melanopic EDI ~100 lx). Further, in an office study of dayworkers where the melanopic EDI of control condition was already high (~400 lx) further increases (melanopic EDI ~750 lx) associated with the use of an 8000 K lighting system appeared to prevent the normal seasonal advance in sleep timing[74]. While the latter could be considered beneficial, as it enhances circadian alignment to the working day, long-term effects of decoupling from seasonal environmental rhythms is to date unclear. Given these data, future research is warranted to identify the potential beneficial and adverse effects on human physiology, cognition, behavior and health of electrical lighting that greatly exceeds our intensity recommendations.

In addition to reduced daytime light exposure, increased exposure to electrical light in the evening and night is commonly considered to exert adverse effects on sleep, circadian rhythms, and health outcomes [6-9,75-77]. Indeed, even relatively low levels of light in the sleep environment (conservatively, melanopic EDI >3 lx) have been associated with impaired sleep and increased incidence of diabetes in large cohort studies[75,76]. Further, typical evening light levels fall comfortably within the range where significant non-visual responses would be predicted from laboratory studies[78]. For example, a significant source of evening light exposure is from visual displays, which in the absence of any other illumination, can provide melanopic EDI levels of >70 lx[79,80] (above the typical level of exposure required to produce half-maximal subjective alerting, melatonin suppressing and circadian phase-shifting responses in laboratory studies; Fig. 2). Indeed, findings from a number of studies have shown that light from modern visual displays is sufficient to reduce the evening rise in melatonin and increase alertness/impair sleep[79-82]. Moreover, manipulations that reduce exposure to short wavelength light from such displays has, in some laboratory studies, been found to lessen these effects[81,82] as have selective reductions in melanopic output[34]. There have not yet been large scale longitudinal field studies on how effective such manipulations might be, although it is noteworthy that the reductions in melanopic radiance achievable simply by adjusting the spectral content of current visual displays are modest (~50% decrease). As such, we expect that such approaches will be most beneficial when combined with other strategies to minimise

evening illumination (e.g. dimming of screens and ambient lighting). In addition, the potential protective role of adequate daytime light exposure to attenuate adverse effects of evening and nighttime light exposure on circadian physiology requires future research.

Special cases and exceptions

While the current recommendations are intended to be widely applicable, the scientific underpinnings primarily derive from studies of neuroendocrine, circadian, sleep and behavioural responses to ocular light exposure in healthy young adults. Even among this group, findings from a recent laboratory study show significant (>10-fold) inter-individual variations in sensitivity to white-light induced suppression of the evening rise in melatonin[52]. The physiology underlying this variability is largely unknown. The magnitude of non-visual responses to light depends on age, with those in young children being larger and those in older adults tending to be smaller when compared to young adults[83-87]. These observations may, in part, reflect age-related differences in the amount of light reaching the retina (due to changes in pupil size and lens transmittance), although more direct changes in sensitivity or amplitude may also be involved. Changes in light exposure in line with the current recommendations are still certainly expected to be of general benefit to both young[65-68,80,82] and older individuals[71-73,75,76]. It remains possible, however, that select groups may further benefit from higher daytime (e.g., the elderly) and/or lower evening exposures (e.g., children) than indicated in the recommendations. Similarly, disruptions to sleep and circadian rhythms are commonly associated with many disorders and disease states[6,88]. While adjusting light exposure may be of benefit in some or all of these conditions, further research will be required to determine whether alterations to the recommended thresholds will be required for such individuals.

In addition to the points above, a particular challenge in optimising light exposure to benefit health and performance relates to shift-workers. Current light exposure advice for night shift workers is still not mature[89] and we want to stress that the present recommendations are not intended for this purpose. There is certainly evidence that increasing melanopic light levels in the work environment can improve alertness and performance in shift workers[90-93]. Important benefits such as these do, however, need to be weighed in the context of potential disruptions to circadian alignment and chronic effects on health[6-9]. Addressing these important questions, remains a key area for future investigation and shift-work-related consensus guidance on best practice.

As discussed in more detail below, it is also essential that any changes to light exposure intended to adjust melanopsin-dependent physiological responses do not compromise visual requirements. For example, the elderly may need brighter lighting than recommended above to move safely between the bedroom and bathroom at night. In many cases, such issues may be addressed by using lighting with an appropriate spectral composition (i.e. by using lighting with a low ratio of melanopic EDI to illuminance; see Fig. 3) and/or lighting designs that avoid direct illumination of the face. Nonetheless, there may be some instances where meeting the requirements for visual performance, visual comfort and safety are incompatible with our recommendations regarding non-visual responses, in which case the former must take precedence.

Finally, while it is possible to comply with the recommended melanopic EDI thresholds specified here solely via exposure to electrical light, there are a number of known and suspected benefits of exposure to broad-spectrum, outdoor, daylight[94-96]. Further, there are other non-ocular beneficial biological effects of outdoor daylight exposure to be considered (e.g,. facilitating production of vitamin D)[97].

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Relationship to existing standards

There are a number of national and international standards that have been developed under rigorous due processes, consensus, and other criteria that are relevant to indoor light exposure in the built environment. In terms of biological safety, there is a recent recommended practice for photobiological safety that provides guidance on ocular and dermal health relative to light exposure from all varieties of indoor lamps and lamp systems (American National Standards Institute/Illuminating Engineering Society; ANSI/IES RP-27-20)[98]. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has also released a recent statement concerning photobiological safety, specifically of light exposure from LEDs[99]. Other existing guidelines, codes and specifications for lighting installations in indoor places primarily concentrate on visual function, including visual comfort, visual performance and seeing safely for people with normal, or corrected to normal, vision.

Current specifications within lighting practice are based on illuminance and several additional qualitative and quantitative needs concerning glare, colour rendering, flicker and temporal light modulation, luminance distribution and the directionality and variability (of both colour and level) of light. These specifications are crafted to enable people to perform their visual tasks accurately and efficiently, even for difficult circumstances or extended durations (e.g. Deutsches Institut für Normung, DIN SPEC 67600[100]; ANSI/IES RP-28-16[101]; prEN 12464-1[102]). Together with the focus on energy saving, the existing guidelines restrict the illuminance indoors to levels that are typically at least one order of magnitude below the natural light environment outdoors. This leaves us with an indoor light environment that is potentially sub-optimal for supporting human health, performance and well-being. For example, Comité Européen de Normalisation (CEN) guidelines specify a minimum task plane photopic illuminance of 500 lx for writing, typing, reading and data processing tasks. When just meeting this illuminance threshold with standard (low melanopic efficacy) lighting, typical (vertical) melanopic EDIs encountered across the working day will fall below 200 lx (e.g.[62-64]; Fig. 3A,B).

This publication is centrally based on an internationally balloted standard from the CIE[28] which now provides an accepted framework upon which to derive lighting specifications that optimize visual, circadian, neuroendocrine and behavioural responses to light. The corresponding expert-led consensus-recommendations for biologically appropriate lighting are reflected in general melanopic EDI thresholds for various times of day/night. The recommendations presented here are intended to be achievable within the constraints of other relevant lighting guidelines (e.g. via lighting of appropriate spectral composition; Fig. 3) and to provide a sound scientific basis for the formal development of recommended practices in light and lighting from national and international standards organizations (e.g. ANSI, CIE, DIN, IES and ISO).

FUTURE DIRECTIONS

The recommendations outlined here are derived from a synthesis of several decades of research into the biology regulating circadian, sleep, physiological and cognitive responses to light and their practical implications. There is, without question, evidence that the use of melanopic irradiance as a model for the spectral sensitivity of such responses represents a simplification of the underlying biology. Although, as an aside, we note that this is true also for the established and widely used, photometric quantities (luminance and illuminance) that are currently applied to quantify conventional 'brightness'. Nevertheless, we leave open the possibility that a deeper understanding of rod and/or cone contributions to physiological responses will reveal multi-photoreceptor models of spectral sensitivity that may allow a more accurate prediction of circadian, sleep, neuroendocrine and cognitive responses. The contribution of rods to such responses is an important topic for research in its own right, Including rods in any future metric is, however, unlikely to materially improve its accuracy since

rods and melanopsin have rather similar spectral sensitivity. Conversely, cone spectral sensitivity is quite distinct from melanopsin and has the potential to substantially refine metrics for circadian and neurophysiological responses. In particular, future work may reveal specific lighting conditions that maximise cone influence to produce practically relevant modulations in non-visual responses to light. At present, however, existing evidence indicates that the use of melanopic irradiance would not lead one to substantially over- or under-estimate biological and behavioural effects for the types of light exposure that are typically encountered across daily life[29-32,34-37].

Further research into the factors influencing individual differences in the sensitivity of melanopsin-mediated responses to light exposure may make it possible to tailor guidelines to specific groups or even individuals. For the time being, our recommendations are derived from group data that must incorporate much of this variability. As such, it is expected the recommendations for daytime and the sleep environment should be broadly applicable and strongly engage relevant circadian and neurophysiological responses for the vast majority of the population. Known, age-related sources of variability are already at least partly accounted for by the inclusion of corrections for changes in lens transmission described in the non-normative appendices of the existing standard[28]. Recommendations for evening light exposure may, however, be modified in the future for certain groups such as young children, which may require lower light levels or dim light for longer than 3 hours before sleep.

The current recommendations are intended to inform lighting design considerations for typical, real-world environments such as offices and other workplaces, schools and colleges, residences, care homes, and in- and outpatient settings. A final point for consideration relates to applications of light therapy for clinical conditions like affective and circadian rhythm sleep disorders, or for purposes such as improving circadian regulation and alertness in night and shift workers or transmeridian travellers experiencing jet lag. The current recommendations are not intended for such uses, but the existing applications of ocular light therapy likely involve the same or similar biological underpinnings as discussed above. Perhaps widespread adoption of the recommendations described here will contribute to a reduction in the prevalence of affective and sleep disorders. More significantly, we expect the scientific framework which informs these recommendations to provide a concrete basis upon which to generate hypotheses to test for the subsequent establishment of optimal light treatment recommendations for clinical and travel applications.

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CONFLICT OF INTEREST

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SWL has received consulting fees from Atlanta Falcons, Atlanta Hawks, BHP Billiton, Delos Living LLC, EyeJust Inc., McCullough Hill Leary PS, Noble Insights, OpTerra Energy Services Inc., Pegasus Capital Advisors, Phillips Lytle LLP, Plan LED, Rec Room, Serrado Capital, Slingshot Insights, Stantec and Team C Racing. He has current consulting contracts with Akili Interactive, Apex 2100 Ltd, Consumer Sleep Solutions, Headwaters Inc., Hintsa Performance

AG, KBR Wyle Services, Light Cognitive, Lighting Science Group Corporation/HealthE, Look Optic, Mental Workout/Timeshifter, Paul Weiss Rifkind Wharton & Garrison LLP, Six Senses, and View Inc. SWL has received unrestricted equipment gifts from Bionetics Corporation and F.LUX Software LLC; a fellowship gift from Stockgrand Ltd; has equity in iSLEEP, Pty; royalties from Oxford University Press; honoraria plus travel, accommodation and/or meals for invited seminars, conference presentations or teaching from Estée Lauder, Ineos, Informa Exhibitions, MIT, Roxbury Latin School, and Teague; travel, accommodation and/or meals only (no honoraria) for invited seminars, conference presentations, teaching or editorial duties from DIN, Emory University, Lightfair, SLTBR, Solemma and Wiley. SWL has an ongoing investigator-initiated grant from F. Lux Software LLC and a Clinical Research Support Agreement from Vanda Pharmaceuticals Inc. SWL holds a process patent for 'Systems and methods for determining and/or controlling sleep quality', which is assigned to the Brigham and Women's Hospital per Hospital policy, and 'Method and system for generating and providing notifications for a circadian shift protocol' held by Mental Workout Inc. SWL has served as a paid expert in legal proceedings related to light, health and work patterns. SWL was the Program Leader for 'Safety and Productivity Improvements' in the CRC for Alertness, Safety and Productivity from 2015-2019, through a part-time Adjunct Professor appointment at Monash University, Australia. SWL's interests are reviewed and managed by Brigham and Women's Hospital and Partners HealthCare in accordance with their conflict of interest policies.

RJL and TMB have received research funding from Signify (formerly Philips Lighting).

RJL, LP, LJMS and MS have served as members of the CIE Joint Technical Committee 9 on the definition of CIE S 026:2018. These were unpaid roles.

JPH, MM and SNP report no conflicting interests.

JOH, In addition to paid employment with Public Health England, is Vice-President Standards of the CIE, a member of the Scientific Expert Group of the International Commission on Non-Ionizing Radiation Protection and a number of their Project Groups, Co-Convenor of an ISO committee on Integrative Lighting, a member of two committees of the Illuminating Engineering Society of North America, Convenor of an IEC committee and a member of a Core Group for the World Health Organization, all as unpaid roles.

LP served as the CIE reporter to CIE TN 003:2015 on the first Manchester Workshop in 2013, is currently serving as Director and as Secretary of the CIE Division "Photobiology and Photochemistry", as the CIE reporter on the CIE S 026 Toolbox (doi.org/10.25039/S026.2018.TB), as a member of CIE Joint Technical Committee 14 (working with ISO Joint Working Group 4) on Integrative Lighting, and as the CIE reporter on the second Manchester Workshop 2019 (attended by all the authors), all as unpaid roles

LJMS's full time position at Eindhoven University has been partially funded by Signify, he is also active in various unpaid roles within the International Commission on Illumination (CIE).

DJS is a co-inventor on issued patents (EP1614441A1 and WO2015052207A1).

CV is an unpaid member of the Circadian Light Therapy (Inc.) and the Chronsulting Scientific Advisory Boards. In addition, CV's research and scholarship is funded by the University of Colorado Boulder, the Colorado Clinical and Translational Sciences Institute, the National Institutes of Health, and the Department of Energy.

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KPW reports during the conduct of the 2nd International Workshop and preparation of this manuscript being a board member of the Sleep Research Society; chair of the American Academy of Sleep Medicine Clinical Practice Guideline for the Treatment of Adults with Shift Work Disorder and Jet Lag Disorder Workgroup; receiving research support from the NIH, the Office of Naval Research, the PAC-12 conference, and consulting for Circadian Therapeutics, LTD., Circadian Biotherapies, Inc. Philips Respironics, U.S. Army Medical Research and Materiel Command-Walter Reed Army Institute of Research outside the submitted work.

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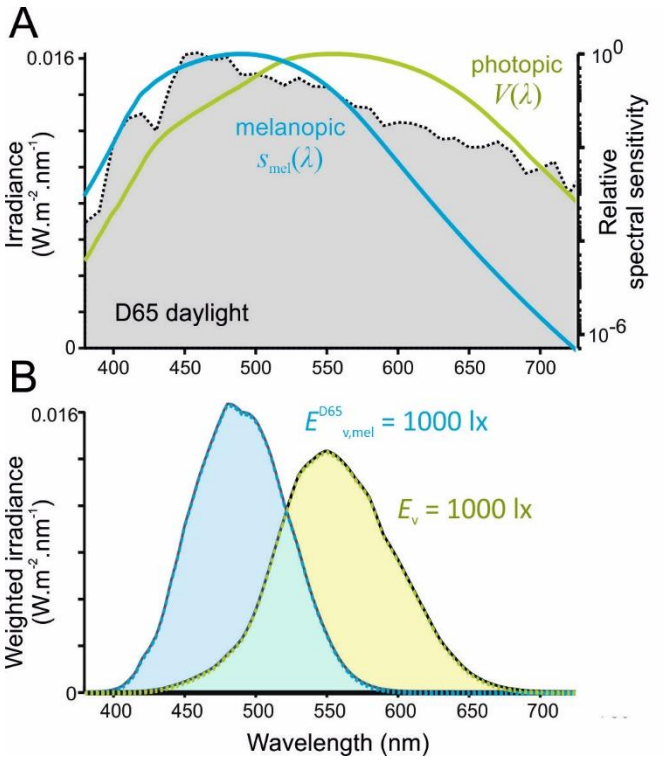

Figure 1. Differences in visual and non-visual spectral sensitivity formalised in the SI-compliant system for quantifying ipRGC-influenced responses to light. Panel **A** illustrates the melanopic action spectra ($s_{mel}(\lambda)$ with peak sensitivity at 490 nm (following correction for the transmission properties of the standard 32-year old human lens) and the photopic (spectral luminous efficiency) function, $V(\lambda)$, superimposed on the spectral power distribution of standard daylight (CIE illuminant D65). Panel **B** illustrates the weighted spectral power distribution for spectrum in **A** multiplied by the photopic and melanopic efficiency functions at 1000 lx for illuminance (E_v) and melanopic equivalent daylight illuminance (melanopic EDI; $E^{D65}{}_{v,mel}$). Sensitivity curves and full details of calculations are available from the CIE S026 standard[28].

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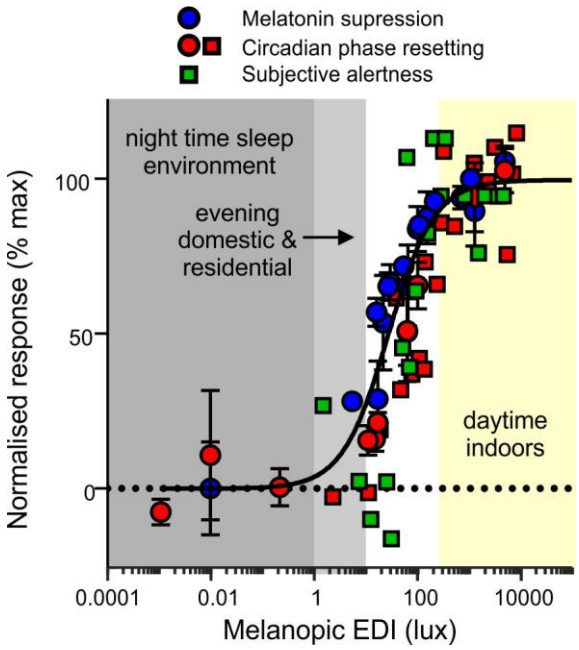

Figure 2. Recommendations for melanopic light exposures in relation to the sensitivity of melatonin suppression, circadian phase resetting and subjective alerting responses. Data are derived from laboratory-studies (studies without the use of pupil dilators) investigating the impact of long exposures (>2 h) to primarily broadband light sources on melatonin[42,49-51,53,103,104] as analysed in[32]. Circles represent group means with SEM, squares data from individual subjects. Shaded areas reflect the consensus recommendations of the 2nd International Workshop on Circadian and Neurophysiological Photometry for sleep, evening and indoor daytime environments.

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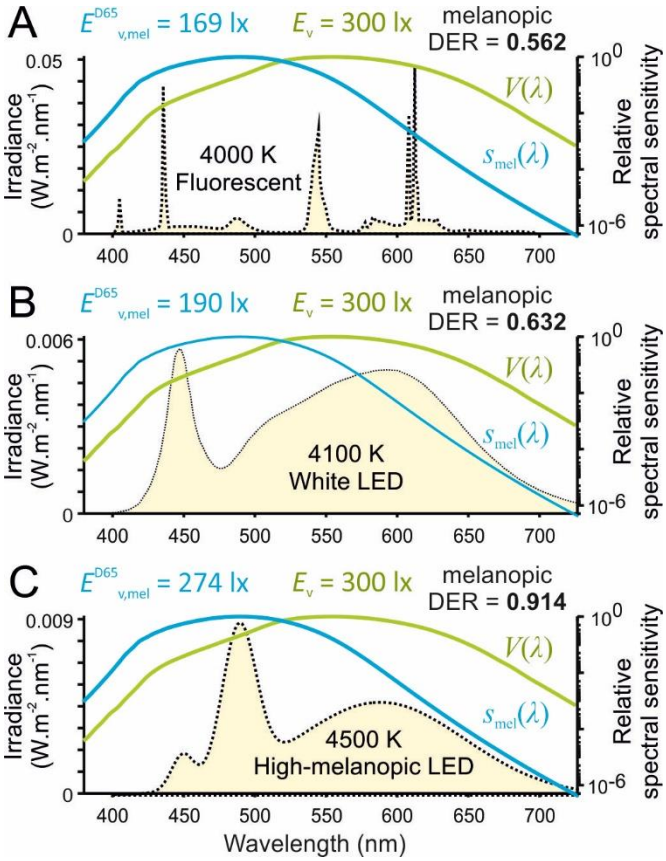

Figure 3. Impact of divergent spectral composition of electrical white light sources on melanopic efficiency. Panels **A**-**C** illustrate spectral power distributions (yellow) for commonly encountered fluorescent (A) and LED-based (B) white light sources, and for a high melanopic content LED source of similar correlated colour temperature (**C**) achievable with current technologies. Melanopic (blue) and photopic (green) spectral efficiency functions are shown for reference. Photopic illuminance (E_v) and melanopic equivalent daylight (D65) illuminance ($E^{D65}_{v,mel}$) for each spectrum is provided above, along with the melanopic efficiency for that light source (Melanopic daylight (D65) efficacy ratio; melanopic DER), defined as the ratio of melanopic irradiances for this source to that for a D65 source at the same photopic illuminance). Note, in this example, all three sources provide a photopic illuminance of 300 lx but vary in melanopic EDI, due to the relatively low melanopic DER of conventional white light sources. Employing light sources with appropriately engineered spectra, therefore, provides a useful route to optimize non-visual responses to light within the constraints imposed by any visual requirements and regulations.