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TECHNICAL NOTE

Second International Workshop on Circadian and Neurophysiological Photoreception

CIE TN 015:2023

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The following 18 members of the Second International Workshop on Circadian and Neurophysiological Photoreception, 2019 (“the workshop”) took part in the preparation of this Working Draft Technical Note.

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Second International Workshop on Circadian and Neurophysiological Photoreception

Summary

This Technical Note reports on the proceedings and consensus of the invited experts of The Second International Workshop on Circadian and Neurophysiological Photometry, 2019. This workshop acted on the basis of a consensus of the participants, who are also the advisers to this report.

The two papers that followed from this workshop in 2020 and 2022 are cited in the report, and these take precedence for the interpretation of its scientific consensus, which is also set out here. Although Technical Notes can also include the personal views of the reporter, the contents of this report have been agreed with all the advisers, unless explicitly stated. The consensus and recommendations summarized in this Technical Note do not necessarily represent the views of the CIE in relation to circadian and neurophysiological photometry.

1 Introduction

The focus of the 2019 Manchester (UK) workshop ("the workshop") (Brown et al., 2022) related to making recommendations about how to optimize light exposures for promoting circadian health, well-being and performance. It identified the central role of melanopsin-based photoreception in the eye for predicting human physiological responses to light. Its outputs are intended to provide an interpretation for governments, the lighting community and professionals working in public health, whilst highlighting the importance of scientific advances and the growing evidence base in this area.

This Technical Note summarizes the proceedings and consensus of the Second International Workshop on Circadian and Neurophysiological Photometry held in 2019 in Manchester. CIE TN 003:2015 (CIE, 2015), Technical Note on the First International Workshop on Circadian and Neurophysiological Photometry, 2013, dealt with the first workshop in a similar way. Publications following from both workshops are set out in Table 1.

The workshop considered new evidence about what constitutes healthy light and lighting, and the workshop's recommendations are deliberately built on a measurement system introduced by the 2013 Manchester workshop ("the first workshop"; see CIE TN 003:2015). CIE later formalized this system as the international standard CIE S 026:2018 (CIE, 2018). The 2019 workshop provided a key next step by agreeing the first explicit international consensus recommendations for light exposures that support healthy daily variation in physiology, sleep, and alertness. The recommendations are specified in terms of appropriately quantified numerical threshold levels and associated timings for when light should be sought or avoided.

The three main recommendations from the workshop below deal with daily exposures to light for healthy day-active adults (aged between 18 and 55 years), using exposure thresholds as a function of time-of-day (Brown et al., 2022). The thresholds are expressed in terms of the melanopic equivalent daylight (D65) illuminance (CIE, 2018) (melanopic EDI, in lx) measured at eye height and in the direction of view. The workshop recommendations are described below (for terminology, see Table 2).

- **During the daytime the recommended minimum melanopic EDI is 250 lx**, using daylight if available or, where addition of electric light is required, via white light with a high melanopic daylight (D65) efficacy ratio (melanopic DER[1]).

[1] During the daytime, Brown et al. (2022) recommend "polychromatic white light [with] a spectrum that, like natural daylight, is enriched in shorter wavelengths close to the peak of the melanopic action spectrum." Melanopic DER is the ratio of melanopic EDI to photopic illuminance, sometimes called the "M/P ratio".

- **During the evening the recommended maximum melanopic EDI is 10 lx**, starting at least three hours before bedtime. To achieve low melanopic EDI values, using electric lighting with a low melanopic DER is advisable.
- **During the night, the recommended maximum ambient melanopic EDI is 1 lx**, and the sleep environment should be as dark as safely possible, reverting to the 10 lx maximum melanopic EDI for unavoidable activities where more light is required for vision.

These three recommendations relate to the shaded areas shown in Figure 1 (to blue, grey and dark grey, respectively), and derive from an interpretation of the data that are summarized in that Figure.

Whilst there are exceptions to these guidelines, for a range of practical reasons, the workshop's consensus view is that these principles now have a sufficiently reliable evidence basis, drawn from good quality scientific research, and that these initial recommendations can be applied to architectural and integrative lighting designs, as well as lifestyle advice.

Table 1 — Timeline of key publications following from the 2013 and 2019 Manchester workshops

The First International Workshop on Circadian and Neurophysiological Photometry was held in Manchester (UK) on 10-12 January 2013.	
January 2014	A review paper (Lucas et al., 2014) setting out the first workshop consensus, with research and α-opic metrological recommendations. The 2014 "irradiance toolbox" first supported the use of five α-opic irradiances and α-opic equivalent illuminance quantities relating to non-visual photoreception in humans.
July 2015	A Technical Note (CIE, 2015) interpreting the first workshop consensus. This included the second, SI-compliant, irradiance toolbox as a CIE publication.
November 2018	An International Standard (CIE S 026/E:2018, http://doi.org/10.25039/S026.2018) for the α-opic measurement system, "CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light." The standard retained the approach of the recommendations of the first workshop, harmonized rod and cone action spectra with existing CIE publications, and adopted the CIE standard illuminant D65 as the reference daylight spectrum for normalizing α-opic equivalent photometric quantities, via five new α-opic efficacy constants.
March 2019	A CIE "α-opic toolbox" based on CIE S 026:2018 (CIE, 2018) to replace the irradiance toolbox. The 2019 beta-version and user-guide are superseded by maintained CIE versions (Schlangen et al., 2019): (http://doi.org/10.25039/S026.2018.TB, http://doi.org/10.25039/S026.2018.UG).
May 2019	The 9th edition of the Système International (d'unités) (ISBN 978-92-822-2272-0), incorporating a CIE reconciliation of the photon and energy systems of radiometry (from the conversion basis in the first irradiance toolbox)
The Second International Workshop on Circadian and Neurophysiological Photometry was held in Manchester (UK) on 21-23 August 2019.	
October 2019	The latest CIE Position Statement on Non-Visual Effects of Light (CIE, 2019). Its guidance, informed by the 2019 workshop, is for high melanopic EDI during the day, and low melanopic EDI at night, for people with a regular, day-active schedule.
April 2020	A meta-analysis of ecologically valid studies of physiological responses to light exposures (Brown, 2020) to investigate the explanatory power of the five spectral sensitivities in CIE S 026, the follow-up to one of the workshop papers
March 2022	A review paper setting out the latest workshop's consensus (Brown et al., 2022), with recommendations about healthy exposures to light.

2 Background

Day-in and day-out, many biological processes in the human body rise and fall in patterns, that repeat approximately every 24 h, called circadian rhythms (circadian literally means “about a day”). Several links between health and circadian rhythms are already known, sleep regulation being a good example, with many more yet to be revealed. The growing field of circadian health is concerned with promoting the proper functioning of the molecular daily timing mechanisms (clocks or oscillators) within the human brain and body that regulate many aspects of physiology and behaviour, including metabolism, and immune and cardiovascular function.

To promote healthy circadian rhythms, it is essential to understand and predict how they respond to the environment. Light detected in the eyes provides the circadian system with its primary environmental information about time of day and night across seasons. In 2000, a new photopigment called melanopsin was discovered in the retina of humans (Provencio et al., 2000), and it is centrally involved in this process. The melanopsin-based photoreceptors are called ipRGCs (which stands for intrinsically photosensitive Retinal Ganglion Cells). ipRGCs also process signals they receive from other photoreceptors found in the retina (the rods and cones), combining this information with their own melanopic response to light. The resulting information is transmitted to a range of targets in the brain, including the part of the brain that keeps and interprets circadian time.

Human responses to light through the circadian system, and through other brain targets of ipRGCs, are sometimes known as ipRGC-influenced responses to light (IIL responses) (CIE, 2018). Given that visual responses are less dependent on ipRGCs, ipRGC-influenced responses have also been described widely as “non-visual” or “non-image-forming” responses to light, but the terms can be ambiguous when used out of context. The spectral sensitivities of rods and the three cone types are also different to that of ipRGCs. Although signals from rods and cones are involved in the circadian system, the evidence suggests that for most practically relevant conditions the spectral sensitivity of the ipRGC photopigment melanopsin alone can predict such responses closely, and better than the rods or any of the three cone types (Brown, 2020).

3 Proceedings of the workshop

The Second International Workshop on Circadian and Neurophysiological Photometry was held in Manchester (UK) on 21-23 August 2019. The workshop was chaired jointly by Professor Timothy Brown (TB) of the University of Manchester and Professor Kenneth P. Wright Jr (KW) of the University of Colorado. It was attended in person by representatives accepting an invitation sent to leading international research groups, on the response of humans to light exposures, with specific expertise in field studies, lighting standards and individual level characteristics determining variability in responses. Professor G. C. Brainard (GB), one of the two joint chairs of the first workshop, was unable to attend in person, but joined via video link from the US.

TB and KW welcomed the participants and outlined the format for the workshop. The aims of the workshop were to move forward from the first workshop’s emphasis on research and measurement methods and discuss if the current data supported making health-related recommendations about light exposures. The intended target audiences include the public, lighting and architectural designers, and governments and organizations responsible for public health and lifestyle advice. This meeting was two days shorter than the first workshop, with a larger group of experts. Although it was not guaranteed at the outset, a consensus position was reached.

To start the workshop, several attendees presented an overview and preliminary results from their latest research projects. Group discussions were allowed freely during this phase. A brief summary of each presenter’s data is listed below. Although more space is given to the first two presentations, as will be explained, these are still considerably shortened, and the discussions are not reported here:

Luc Schlangen (LS): LS presented human experimental evidence that prior light influences subsequent responses to light non-additively on the same day; light exposure in the early evening had reduced the effects of late evening exposure on melatonin suppression, for example (te Kulve et al., 2019).

LS outlined the five-photoreceptor α-opic metrology International Standard that followed the first workshop's recommendations (CIE, 2018; Lucas et al., 2014). He covered SI compliance aspects and the new "equivalent daylight" quantities expressed in the existing photometric units, such as melanopic equivalent daylight (D65) illuminance (CIE, 2018) (melanopic EDI, expressed in lx). The standard had defined the term IIL responses to remove the ambiguity in the terms "non-visual" or "non-image-forming" responses, and defined two types of α-opic efficacy ratios (see Table 2) for characterizing spectral properties, more suitable than using correlated colour temperature (CCT) for IIL responses.

Melanopic irradiance (unit: $W \cdot m^{-2}$) can be calculated using the new standard melanopic action spectrum, according to the normal rules of the SI brochure (BIPM, 2019).

Melanopic EDI is then equal to the illuminance (unit: lx) corresponding to this melanopic irradiance, after substituting the relative spectral distribution of the CIE standard illuminant D65 in place of the true spectral distribution (see Table 2).

No new units are introduced. For instance, "lx" and "lux" should be used without qualifiers, other than stating the quantity, such as melanopic EDI. It is wrong to say "melanopic lux".

Just as light of approximately 555 nm is used to normalize the definition of the lumen for use with $V(\lambda)$, in the new metrology D65 acts solely as a normalization condition suitable for all five α-opic action spectra. Importantly, D65 is not used as a spectral weighting, and takes no part in the α-opic spectral-weighting process.

A detailed discussion of the standard (CIE S 026:2018), is given in Schlangen and Price, (2021).

In another study, LS showed two chromatically equal LED lamps, with equal CCT of 2 700 K, had been designed with different ratios of melanopic EDI to photopic illuminance (Souman et al., 2018). This difference in their melanopic daylight (D65) (CIE, 2018) efficacy ratio (melanopic DER) was hypothesized to produce different IIL responses, and this was confirmed by the experiment (melanopic DER was also sometimes referred to in discussions as the "M/P ratio", see Table 2). LS emphasized that CCT is no longer a good metric to predict IIL responses, as it is possible to engineer lamps with the same CCT that differ in their melanopic DER. This meant that melanopic DER should be used in the future to characterize spectra in terms of their efficacy, for eliciting IIL responses, relative to measures that reflect their visual efficacy, such as illuminance.

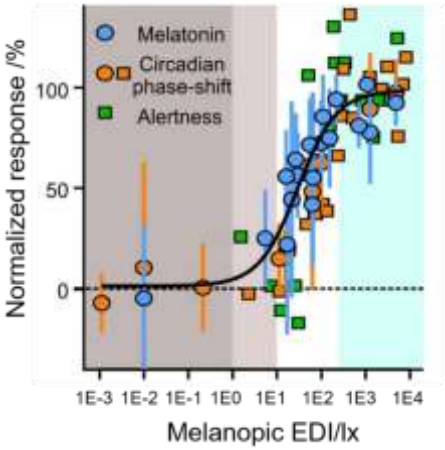
It was a generally agreed baseline understanding at the start of the workshop that (i) an exposure with a greater irradiance at the eyes would produce greater neurophysiological responses (whatever the spectrum of the light source, between suitable low and high response thresholds, all other factors being held equal), and (ii) manipulating light irradiance is more practically relevant than manipulating spectral composition.

It was agreed that it was reasonable to say the responses are predicted by melanopsin sensitivity, but this does not necessarily have to mean there is an exclusively melanopic mechanism. This was important, because as well as studying the underlying biology, the workshop aimed to find a practical route to giving advice on exposures. It was also agreed that wording should be included in the workshop recommendations to avoid people neglecting the importance of other responses to optical radiation, including ultraviolet radiation (UVR) and infrared radiation (IRR).

Timothy Brown: TB presented his evidence (see Clause 4). Firstly, however, he discussed data in mouse studies (e.g. Walmsley et al., 2015) which suggested that colour had a signalling role in the circadian responses. The exposure scenarios and generalizability of these data to

recommendations in humans were disputed in discussion, due to the possibility that behaviour elicited by visual responses was also contributing. Notwithstanding the consistency of the results, it was agreed that there was insufficient evidence to rule out this possibility.

TB's main evidence is also presented in Figure 1. He showed in humans that melanopsin was the best single opsin predictor of human melatonin suppression, circadian phase resetting, and self-reported alerting responses to light. He also showed in humans that it was sufficiently reliable for different conditions and assays in real world conditions to be used as a basis of recommendations, with a range of responses well within melanopic EDI of 1 lx to 1 000 lx. There was some divergence of response sensitivities at lower intensities of melanopic EDI, and at shorter durations, in several animal and human studies.



NOTE Data for melatonin suppression, circadian phase resetting, and self-reported alerting responses to light are shown in blue, orange and green respectively, with both group data (circles, mean ± SD) and individual data (squares). For the weighted best fit 4-parameter logistic curve (dark line), normalization fixes two of the parameters. Conditions meeting the consensus recommendations are shaded to show how the latter were based on the data (see Introduction, Brown, 2020 and Brown et al., 2022).

Figure 1 — Normalized responses for human eye exposures of >2 h during evening and night can be described using melanopic EDI, in adults without pharmacologically dilated pupils

TB's analysis combined with LS's melanopic DER experiment, was persuasive to the workshop participants, and there was a strong consensus even from this early stage in the proceedings. It was widely agreed that (i) for real world day-active human exposures (such as exposure durations longer than a few minutes without pharmacological control of pupil size), the neurophysiological responses are much more clearly explained by melanopsin, and (ii) melanopic EDI was suitable to frame recommendations by the workshop on light exposure and/or related lighting design questions.

CIE subsequently acted on the interim workshop consensus to issue a position statement in 2019 promoting the wider use of melanopic EDI in lighting design (CIE, 2019).

Robert Lucas (RL): As TB's presentation had produced much discussion, RL curtailed his own contribution, only speaking briefly. In studies with a visual display in the form of a video projector capable of melanopic tuning, both alertness and melatonin suppression had been modulated with no visual changes to the stimulus (Allen et al., 2018). As hypothesized, these responses were regulated by only changing the melanopic component of the α-opic components of the viewed spectra from the videos, a finding similar to the LED exposure data showed by LS.

Mirjam Münch (MM): MM presented on the impact of light during the day on wake and sleep function from several groups, including a study on the effects of adaptation interventions of ≤3 h on pupil and EEG responses to a pupillometry light pulse (de Zeeuw et al., 2019). The EEG response metrics can evaluate responses to daytime light exposure, and represent objective measures related to sleepiness. Overall, the various studies showed similar trends to other visual and non-visual data, and combining the de Zeeuw et al. (2019) paradigm with metameric light sources opens up new lines of enquiry.

At this point, TB proposed that the use of melanopic EDI was emerging as a basis for the workshop to make recommendations, and that we needed to consider what limits were appropriate for daytime and evening exposure. As chairs, TB and KW agreed on this, and the participants were encouraged to focus their discussions during subsequent presentations on these questions, in the interest of the limited time available, and there would be time later to discuss exceptions and clarify the scope and context for recommendations.

Steven Lockley (SL): SL presented next, emphasizing the importance of long exposures and prior light adaptation, and making a case for a spectral ratio approach to lighting and design standards, using melanopic DER. He showed evidence as far back as 2003 (Lockley et al., 2003), confirmed in 2010 (Gooley et al., 2010) and in more recent unpublished work, that the cone component of responses diminishes with duration for human melatonin suppression, and circadian phase resetting. If a model were needed for shorter durations, then either a two-channel melanopic-photopic model or a three-channel model adding in S-cone responses would possibly serve better.

SL also proposed the concept that light considerations should reflect the function of the space. In places where people do not sleep (e.g. schools, offices) and just need to be alert, then a single high melanopic lamp is sufficient. In places where people sleep (e.g. homes, hospitals), then the same high melanopic lamp is sufficient for daytime use, but SL proposed that low melanopic light is required in the evenings before sleep, and this can be simply achieved through two different lamps (e.g. ceiling and table lamps).

SL put forward melanopic DER lighting thresholds of melanopic DER > 0,80 for daytime lighting, values similar to the CIE standard illuminant D65, and melanopic DER < 0,35 for evening lighting, similar to artificial sources that have already long been used in people's homes.

As this presentation proposed departing from setting absolute thresholds for melanopic EDI, there was some discussion. Czeisler, C. (CCz) was concerned about the potential for the melanopic DER advice, if used alone, to be misapplied, noting that misapplied nutritional advice had resulted in the modern epidemic in obesity and diabetes. Till Roenneberg felt that guidance for daytime light exposures should relate to an individual's actual level of prior exposure. SL himself had experienced the difficulty of using thresholds with the lighting industry. Using melanopic DER also raised the question of how photopically defined energy efficiency would interfere with implementing the advice. It was generally perceived that these and other discussion points showed the potential for a good deal of nuance, and that the workshop should aim to make the simplest step first in its recommendations.

Manuel Spitschan (MS): MS presented silent substitution techniques, which isolate the response of one photoreceptor channel, e.g. melanopsin, by ensuring the stimuli are matched for other photoreceptor types (in this example: the cones). Silent substitution and related techniques have a long history in vision science (Spitschan and Woelders, 2018). While now employed to target melanopsin selectively for non-visual studies, this approach is identical to

the concept of metamerism in previous visual work. Both metamerism and silent substitution take advantage of the phenomenon of univariance; due to univariance, the response of a single photoreceptor-type only carries information about the aggregated stimulus intensity based on its spectral sensitivity, but not about the wavelength distribution of the incident photons. Hence, two carefully designed different spectral distributions can elicit the same responses in any number of photoreceptor types simultaneously. This freedom for differences in the spectral distribution can then be manipulated to vary the stimulus in the target channel, and observed physiological effects can be attributed to the photoreceptor in question. The degree of freedom for melanopsin reduces to a factor of just over three when the cones are matched (Spitschan and Woelders, 2018).

Stuart Pierson (SP): SP's talk recapped the first Manchester Workshop in 2013. He also explained the light environment has further complexity in terms of the radiant field as theoretically captured using hyperspectral images in the same five α-opic channels. Spectral differences in practical light exposures accounted for up to half a log unit (a factor of 5, for example), compared to the absolute range of stimuli of about 3 log units (a factor of 1000, for example).

Celine Vetter (CV): CV argued that the next step for the chronobiology research community was the application to public health. To do so, recommendations for healthy light exposure profiles are necessary, as are reliable individual-level light exposure measurements over time. On the question of how to measure light exposure day and night for several days, i.e. in order to compare the actual exposures with our ideas about them, she explained wearables or dosimeters usually do not capture the correct directional information. She showed a study demonstrating most known dosimeters also did not provide spectrally matched data for any α-opic channels (Price et al., 2017). Inter-individual measures, however, possibly have a useful role in intervention studies. CV also made proposals for a standard in circadian dosimetry.

George Brainard (GB): GB presented over video link, on differences in sensitivity, primarily due to age differences in lens transmittance, and how to approach recommendations for the young and old. He felt lighting design should be specific to the age of building occupants. Lens transmittances across three age groups (N = 81) have been published (Brainard et al., 1997). It remains a priority for him and his colleagues to publish an additional 170 lens transmittances that have been collected.

John Hanifin (JHan): JHan described an investigation into spectral opponency effects in human melatonin regulation. The hypothesis had been that adding 560 nm monochromatic light would down-regulate the responses to monochromatic stimuli at 460 nm and 500 nm. The control-adjusted plasma melatonin change scores showed a nonsignificant trend (p = 0,08) that, in one possible interpretation, supports the hypothesis of spectral opponency. DS noted that, in her work, light at 627 nm had had no effect when added to light at 479 nm.

Ken Wright Jr (KW)**:** KW presented last, with sleep and melatonin data from camping vs modern environments, collected in Boulder (USA), tracking the differences at weekends during winter and summer. There were similar data from Stockholm (Sweden), from camping vs living in modern lifestyle contexts, for entire 7-day weeks in extreme light dark cycles (dark periods of around 3 h 20 min). In all cases, the camping environments reduced variabilities and advanced melatonin offsets, which in modern environments were an average of two hours after sleep offset. This showed the potential for great benefits from light, as the melatonin offset had been associated with the lowest point of human performance in multiple past studies (e.g. Wright et al., 2013).

KW also presented data on global and diffuse irradiance collected at Boulder. The range of conditions at sunrise and sunset, in terms of the melanopic EDI, corresponded closely to the main range over which the human responses to melanopic EDI increase, as TB had shown earlier, i.e. 1 lx to 1000 lx.

Detailed Discussions: After lunch on the first day, the two questions, and the various sub-questions, guiding subsequent discussion were set as follows, with Q1 to be taken on first:

Question 1: Can we define practical recommendations for light exposure using melanopic EDI?

- What is the range for maximal and minimal responses?
- What levels are acceptable during the day and night?
- What variance is there between response types and which responses matter most?
- What variance is there between individuals, how can it be dealt with or predicted?

Question 2: When is reporting melanopic EDI not as reliable, i.e. when do rods and cones matter?"

John O'Hagan added that CIE would consider the workshop as providing a scientific view that would then allow CIE to follow up with any more formal requirements such as those in International Standards. The rest of this report is simply concerned with the outcome of the workshop, and not the detail of the discussions.

4 Meta-analysis of responses to light

As the presentation of a meta-analysis given by TB was agreed to be an accurate and relevant summary of the evidence that was relevant for setting recommendations, he was asked to consider publishing it separately, so that a pre-print would be available to be cited as a basis for a workshop consensus paper (Brown, 2020; also see Allen et al., 2018; de Zeeuw et al., 2019; Gimenez et al., 2016; Nowozin et al., 2017; Prayag et al., 2019; Price, 2014; Souman et al., 2018; Spitschan, 2019).

The full analysis considered insights available from a range of published work evaluating relevant responses to appropriately defined light exposures (see Brown, 2020), However, a key requirement for elements of the meta-analysis which directly informed recommended thresholds was that a study should be considered ecologically valid to be eligible for inclusion. In practice, this meant the participants had to be healthy adults, with constant conditions for the experimental exposures to light, to allow for an adequately powered meta-analysis, and data were not included if subjects' pupils were pharmacologically dilated or if the durations of experimental exposures to light were short (less than two hours).

There was also a requirement for health-related outcome measures in the study, and in practice, the outcomes included were: (1) phase shifting of the circadian clock measured by dim light melatonin onset (DLMO), (2) suppression of synthesis of nocturnal melatonin, and (3) self-reported alertness determined by the Karolinska Sleepiness Scale (KSS).

Finally, the study needed to include enough details of the light exposure to allow the illuminance or the five α-opic equivalent daylight (D65) illuminance (CIE, 2018) values (α-opic EDI values) to be calculated using the standard α-opic action spectra, or the similar action spectra as proposed in Lucas et al. (2014).

Combining studies in healthy adults in "ecologically valid scenarios", the meta-analysis consistently showed the above responses to light are well explained by the melanopsin spectral sensitivity to light. The correspondence is significantly better than using the traditional photopic spectral sensitivity of the spectral luminous efficiency function, i.e. of V(λ), and better than using any one of the four other photoreceptors' spectral sensitivities, i.e. those underlying rod and cone responses.

5 All things melanopic and metrical

As the recommendations set out in Clause 1 are written in terms of the new standard quantity known as melanopic EDI, Table 2 sets out how this is calculated, and relates melanopic EDI to other melanopic quantities and to illuminance using the standard α-opic terminology.

Table 2 — Terminology used in this Technical Note (see (CIE, 2018) for complete standard definitions) using the melanopic component of α-opic radiometry and CIE S 026 equivalent daylight photometry

Quantity, unit Symbol, equation	**Short description**	**Comments, and abbreviation in bold**
Melanopic action spectrum, [1][a] $s_{\mathrm{mel}}(\lambda)$	Relative spectral sensitivity of human melanopsin[b] in vivo	Standard values are in the CIE α-opic Toolbox
Melanopic radiance, W·sr^{-1}·m^{-2} $L_{\mathrm{mel}} = \int L_{\mathrm{e},\lambda}(\lambda)\, s_{\mathrm{mel}}(\lambda)\mathrm{d}\lambda$	Radiance weighted according to the melanopic action spectrum	Examples of weighted irradiance and radiance, calculated with $s_{\mathrm{mel}}(\lambda)$ (see BIPM, 2019)
Melanopic irradiance, W·m^{-2} $E_{\mathrm{mel}} = \int E_{\mathrm{e},\lambda}(\lambda)\, s_{\mathrm{mel}}(\lambda)\mathrm{d}\lambda$	Irradiance weighted according to the melanopic action spectrum	
Melanopic efficacy of luminous radiation, mW·lm^{-1} $K_{\mathrm{mel,v}} = E_{\mathrm{mel}}/E_{\mathrm{v}}$	A quotient equal to melanopic irradiance divided by photopic[c] illuminance E_{v}	**melanopic ELR,** e.g. 1 W·m^{-2}/1 lx = 1 W·lm^{-1}
Melanopic daylight (D65) efficacy ratio, [1][a] $\gamma_{\mathrm{mel,v}}^{D65} = K_{\mathrm{mel,v}}/K_{\mathrm{mel,v}}^{D65}$	The ratio of a melanopic ELR to the fixed melanopic ELR of standard daylight (D65)	**melanopic DER**
Melanopic equivalent daylight (D65) luminance, cd·m^{-2} $L_{\mathrm{v,mel}}^{\mathrm{D65}} = L_{\mathrm{mel}} / K_{\mathrm{mel,v}}^{\mathrm{D65}}$	Luminance of a daylight (D65) reference light that matches a melanopic radiance	**melanopic EDL,** where $K_{\mathrm{mel,v}}^{\mathrm{D65}}$ = 1,3262 mW·lm^{-1}
Melanopic equivalent daylight (D65) illuminance, lx $E_{\mathrm{v,mel}}^{\mathrm{D65}} = E_{\mathrm{mel}}/K_{\mathrm{mel,v}}^{\mathrm{D65}}$	Illuminance of a daylight (D65) reference light that matches a melanopic irradiance	**melanopic EDI,** where $K_{\mathrm{mel,v}}^{\mathrm{D65}}$ = 1,3262 mW·lm^{-1}
Melanopic DER interpreted as the Melanopic/Photopic ratio, "M/P ratio", [1][a] = $E_{\mathrm{v,mel}}^{\mathrm{D65}}/E_{\mathrm{v}}$ = $L_{\mathrm{v,mel}}^{\mathrm{D65}}/L_{\mathrm{v}}$, etc.	The ratio of melanopic EDI to photopic[c] illuminance (M/P ratio is a non-standard term)	**M/P ratio** = melanopic DER = $\gamma_{\mathrm{mel,v}}^{\mathrm{D65}}$

[a] The melanopic action spectrum and the melanopic DER are dimensionless, and have unit one.

[b] Intrinsically-photosensitive retinal ganglion cells (**ipRGCs**) contain **melanopsin**, the photopigment that provides their intrinsic (i.e. melanopic) response to light. ipRGC-influenced responses to light combine the intrinsic (melanopic) response and the four α-opic responses due to the four opsins in the rods and three cone types. Although the **melanopic component** is just one of the five α-opic components, i.e. the one that relates to **melanopsin (**$\alpha = \mathrm{mel}$**)**, it also predicts the combined response in many practical contexts.

[c] **The photopic system** describes a cone-dominated visual response to light, identified in symbols with a single subscript v. It is widely used, so it has not been described here, see (CIE, 2004). $K^{\mathrm{D65}}{}_{\mathrm{mel.v}}$ = 1,3262 mW·lm^{-1} is one of **five α-opic ELR constants** in the CIE α-opic Toolbox that link α-opic metrology to other SI metrologies.

Many scientists and lighting professionals are used to measuring and describing light in terms of illuminance. For those not familiar with the intricacies of the SI (BIPM, 2019), Equation 1 also shows how melanopic EDI can be simply calculated from illuminance and melanopic DER:

Melanopic EDI = Illuminance × melanopic DER

or, respectively, in symbols:

$$E_{\mathrm{v,mel}}^{\mathrm{D65}} = E_v \cdot \gamma_{\mathrm{mel,v}}^{\mathrm{D65}} \tag{1}$$

Melanopic DER can be considered to be an “M/P ratio” (the ratio of melanopic EDI to photopic illuminance). “M/P ratio” is a non-standard term, so there will possibly be other versions in use. For example, the melanopic efficacy of luminous radiation (ELR), which equals melanopic irradiance divided by illuminance (although this is a quotient with unit of watt per lumen ($W \cdot lm^{-1}$), not a true ratio). In contrast, melanopic DER is dimensionless by definition, as the SI unit for melanopic EDI is also the SI unit for illuminance, namely lux.

Where electric and natural lighting are combined, the melanopic DER, measured in the direction of view directly in front of a person’s eyes, will be different to the melanopic DER of the electric light alone, and very often substantially different. If, for example, the illuminance at the eyes is 42 lx measured in the direction of view, and if the total ambient light at the eyes has a melanopic DER of 0,5, then the corresponding melanopic EDI is 21 lx, even if the melanopic DER is 0,3 for example, for the electric light alone.

6 Conclusions: Scope of the consensus statements, and a personal interpretation

The workshop consensus has already been set out in the Introduction (Clause 1). This consensus, together with the full interpretation of the meta-analysis and the totality of the evidence considered leading to the consensus recommendations, is given in the workshop consensus paper (Brown et al., 2022). The recommendations from the workshop are likely to have implications for existing guidelines and regulations on visual function, comfort and safety, but they are not intended to supersede them. Further statements are made here about the scope of the recommendations.

The advice provided is for adult individuals intending to follow a day-active schedule, which is widely agreed to be the normal physiological state for humans. Although the advice relates to principles that can be reinterpreted to other situations with care, no direct advice has been given for children, the elderly, pregnant women, shift-workers, night-workers, long-distance air travellers, and the infirm. Similarly, those who, for whatever reason, feel the need for additional sleep or rest during the day should not feel compelled to follow this regimen until they are sufficiently restored to resume normal activities.

The workshop took simple steps on the basis of the evidence that was sufficiently robust. It also considered new techniques for measuring physiologically relevant responses during the daytime, techniques for measuring personal exposures in greater detail, techniques to isolate and manipulate the responses of individual photoreceptor channels, and how the emerging evidence related to the non-additive effects recommendations. It is difficult to predict to what extent in practical terms future research findings will prove to be at odds with the recommendations. The consensus reflects a widely held judgement that, rather than waiting, at this stage it would be riskier to ignore the strong evidence basis already available when making decisions about lighting and light exposure.

The effects of optical radiation on health are not restricted to vision and IIL responses, and the recommendations are likely to promote other benefits. However, designing indoor light during the day for neurophysiological responses should not be seen as a justification for spending less time outdoors during the day. There is equally no intention for the maximum thresholds that

apply in the evening or at night to be used as a basis for increasing light levels in cases where the lighting is already adequate at those times.

The 2019 workshop consensus is that, through our responses to light exposures, our quality of life and health can be improved by following the recommendations. These recommendations promote achieving melanopically brighter daytime conditions, either indoors or through going outdoors. They also aim to limit unwanted effects on subsequent sleep and circadian timing of any excessive exposure to light indoors in the evening before bed and at night.

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