



RECOMMENDED PRACTICE:
**SUPPORTING THE PHYSIOLOGICAL
AND BEHAVIORAL EFFECTS
OF LIGHTING IN INTERIOR
DAYTIME ENVIRONMENTS**
AN AMERICAN NATIONAL STANDARD



ANSI/IES RP-46-23

RECOMMENDED PRACTICE: SUPPORTING THE PHYSIOLOGICAL AND BEHAVIORAL EFFECTS OF LIGHTING IN INTERIOR DAYTIME ENVIRONMENTS AN AMERICAN NATIONAL STANDARD

Publication of this document
has been approved by the IES.
Suggestions for revision
should be directed to the IES.

**Prepared by the
IES Light and Human Health Committee**



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Preface

This preface is not part of ANSI/IES RP-46-23. It is provided for general informational purposes only.

ANSI/IES RP-46-23 is based on the research citations noted in the Reference section.

This Recommended Practice (RP) does not provide general lighting information that is included in other IES documents. If the reader does not already have this information, it may be obtained as needed from the following current IES Standards:

The Lighting Science Series:

- ANSI/IES LS-1-22, *Lighting Science: Nomenclature and Definitions for Illuminating Engineering*
- ANSI/IES LS-2-20, *Lighting Science: Concepts and Language of Lighting*
- ANSI/IES LS-3-20, *Lighting Science: Physics and Optics of Radiant Power*
- ANSI/IES LS-4-20, *Lighting Science: Measurement of Light – The Science of Photometry*
- ANSI/IES LS-5-21, *Lighting Science: Color*
- ANSI/IES LS-6-20, *Lighting Science: Calculation of Light and Its Effects*
- ANSI/IES LS-7-20, *Lighting Science: Vision – Eye and Brain*
- ANSI/IES LS-8-20, *Lighting Science: Vision – Perceptions and Performance*

The Lighting Practice Series:

- ANSI/IES LP-1-20, *Lighting Practice: Designing Quality Lighting for People and Buildings*
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- ANSI/IES LP-6-20, *Lighting Practice: Lighting Control Systems – Properties, Selection, and Specification*
- ANSI/IES LP-7-20, *Lighting Practice: The Lighting Design and Construction Process*

- ANSI/IES LP-8-20, *Lighting Practice: The Commissioning Process Applied to Lighting and Control Systems*
- ANSI/IES LP-9-20, *Lighting Practice: Upgrading Lighting Systems in Commercial and Industrial Facilities*
- ANSI/IES LP-10-20, *Lighting Practice: Sustainable Lighting – An Introduction to the Environmental Impacts of Lighting*
- ANSI/IES LP-11-20, *Lighting Practice: Environmental Considerations for Outdoor Lighting*
- ANSI/IES LP-12-21, *Lighting Practice: IoT Connected Lighting*
- ANSI/IES LP-13-21, *Lighting Practice: Introduction to Resilient Lighting Systems*
- ANSI/IES LP-16-22, *Lighting Practice: Documenting Control Intent Narratives and Sequences of Operations*

1.0 Introduction and Scope

1.1 Introduction

This Recommended Practice (RP) is the implementation companion to IES TM-18-18, *Light and Human Health: An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses*¹ in that it provides recommendations for translation of the basic science of how light affects visual, circadian, neuroendocrine, and neurobehavioral responses in daytime interior environments, such as those found in schools and offices. IES TM-18-18 reviewed the discovery of melanopsin and the evidence demonstrating that these visual, circadian, neuroendocrine, and neurobehavioral responses can be anatomically—and functionally—distinct from visual responses. This document includes the major advances achieved since the publication of IES TM-18-18 in understanding the physiology by which light mediates circadian, neuroendocrine, and neurobehavioral responses; however, this document does not supplant IES TM-18-18. For a more complete understanding of the topic, this RP should be read as a companion to IES TM-18-18.

The research community has made significant findings relative to lighting that is supportive of physiological

effects in humans. This RP, in providing information relevant to supporting the physiological effects of lighting in interior daytime environments, was created through review and discussion of published research in these areas and is intended to assist design practitioners, owners, manufacturers, governments, public service organizations, and those interested in understanding the process by which physiological effects of light can be accommodated in the built environments designed and maintained for human occupation. The recommendations contained in this publication are intended to supplement, not replace, the lighting design guidelines and standards that support the performance of visual activities in specific applications.

Recommendations contained in this RP are made based on research that is ongoing. Ideas and discoveries that are moving toward consensus will demonstrate significant weight of evidence (identified by the number of published discoveries, the number of laboratories studying the same, and the number of papers in agreement), and new ideas and emerging ideas are recognized by a lower weight of evidence. It is important to remember that all research begins as an emergent idea with a low weight of evidence; during subsequent iterations of this RP, it is expected that some significant-weight research will move toward consensus and that some low-weight research will move into the significant-weight category. (See **Section 5.5 Forecasting Light and Human Health Areas of Interest.**)

1.2 Scope

This RP seeks to translate the circadian, neuroendocrine, and neurobehavioral responses to light, summarized as *physiological responses*, mediated by the intrinsically photosensitive retinal ganglion cells (ipRGCs), with contributions from the classical photoreceptors, for application of white light in interior daytime environments. This RP is designed for use in parallel with the many existing recommendations for lighting intended to optimize visual function. Lighting designers and practitioners should, therefore, continue to ensure that all designs provide sufficient light to meet visual requirements, after which the impact of lighting for physiological responses shall be considered.

This RP does not provide recommendations for visual function in interior daytime environments, as these

recommendations are sufficiently covered by other IES documents, but instead provides complementary recommendations to enhance circadian entrainment, alertness, and performance, within interior daytime spaces through consideration of light spectra and light quantities. This RP is primarily focused on applying the acute alerting effects of light, although discussions of the potential benefits of applying daylight and electric light to the benefit of circadian entrainment and longer-term health outcomes are also included.

This RP applies to the design of lighting for interior spaces that are used during the daytime (defined as 7 a.m. to 7 p.m. for practical purposes) by typical, community-based populations going about their normal day, where alertness is desired and is not considered detrimental. These spaces include but are not limited to: schools, offices, healthcare settings (general inpatient and outpatient), retail settings, prisons, senior environments and care homes, industrial settings, residential settings, and hospitality spaces. Although many of these space types have occupancy and are in operation outside of the daytime hours covered by this RP, the recommendations contained herein are applicable to the daytime hours as defined in this paragraph.

As with any RP, the guidance is not exhaustive and will not be able to address the needs of every individual in every space under every circumstance. There may be individual differences in light sensitivity that result in differences in individual physiological responses, just as there are for visual responses. Because the human response to light is specific to each individual, designers should be aware of the population for which they design, and utilize strategies to accommodate the lighting needs of those with physical, sensory, or cognitive differences. Generally, thoughtful application of best practices benefits all and can accommodate many of these differences.

The principles outlined herein are intended to improve lighting to enhance its physiological benefits during the day in typical environments for the average occupant within a population. Additional, targeted lighting benefits can be delivered in other ways (through task lighting, for example), and examples of these approaches are included in this RP. The literature regarding the

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effects of light on other physiological responses (e.g., melatonin suppression, circadian phase shifting) and at other times of day (i.e., nighttime) is summarized here to provide a broader context for the recommendations that are made. It is important to note, however, that lighting designs that prioritize aesthetic considerations or preferences and do not meet the RP criteria, may create an environment that is not optimized to enhance physiological benefits.

This RP does not apply to clinical application of lighting to treat disorders or diseases such as affective disorders, neurological disorders, circadian rhythm sleep-wake disorders, or fatigue in clinically diagnosed populations. Such therapeutic use of light requires clinical supervision and should adhere to the appropriate normal clinical practice. Similarly, in accordance with current lighting design practice, consideration should be taken when designing lighting for community spaces that are used by patient groups, for example, specialized schools or clinical outpatient areas.

2.0 Definitions

Definitions and technical terms are included in this section to aid the reader in understanding the language and lexicon of the light and human health community, a community that includes photobiologists, neuroscientists, physiologists, health professionals, lighting design practitioners, legislative professionals, and manufacturers. As is the case with all language, conversational terminology for light and human health topics includes terms that are scientifically defined as well as terms that are used colloquially. Some terms are traced to specific technical consensus sources, while other terms are not defined at that level but are used by the professionals listed above. This list includes only terms used in this document, and, with two exceptions for the terms *action spectrum* and *light*, the list does not repeat terms that have official definitions in *ANSI/IES LS-1, Lighting Science: Nomenclature and Definitions for Illuminating Engineering*.²

action spectrum. The quantitative actinic response of a chemical or biological substance or living organism as a function of an appropriate spectral parameter, such as wavelength or photon energy.²

acute responses. (See subheading under *physiological responses to light*.)

alertness. The state of being awake, aware, attentive, and prepared to act or react. Neurologically, alertness corresponds with high-frequency, low-amplitude brain waves resulting from stimulation of the reticular formation.³ A system of nuclei and pathways in the brain participate in the modulation of alertness and sleep.

alpha-opic. Relating to the specified human photoreceptor response due to its opsin-based photopigment, denoted by the symbol α , and its characteristics in the context of ipRGC-influenced responses to light.⁴

Note: The term α -opic encompasses five photoreceptor responses, as set out in Sections 3.1.1 to 3.1.5 of CIE S 026/E:2018.⁵ The symbol α is also used to denote an index for quantity symbols related to these responses. The five α -opic responses are: S-cone-opic, M-cone-opic, L-cone-opic, rhodopic, and melanopic, each of which is defined below.

S-cone-opic. Relating to the human S-cone response due to its photopigment and its characteristics in the context of ipRGC-influenced responses to light.⁵

Note 1: In this standard [CIE S 026/E:2018], S-cone-opic is based on the cone fundamental, as defined in the CIE Fundamental Chromaticity Diagram.⁵ This differs from the approach where the human S-cone response is denoted by the term *cyanopic*, and its spectral sensitivity function is based on an opsin template.^{6,7}

Note 2: The subscript *sc* is used to indicate S-cone-opic quantities.

M-cone opic. Relating to the human M-cone response due to its photopigment and its characteristics in the context of ipRGC-influenced responses to light.⁴

Note 1: In this standard [CIE S 026/E:2018], M-cone-opic is based on the cone fundamental, as defined in the CIE Fundamental Chromaticity Diagram.⁵ This differs from the approach where the human M-cone response is denoted by the term *chloropic* and its spectral sensitivity function is based on an opsin template.^{6,7}

Note 2: The subscript *mc* is used to indicate M-cone-opic quantities.

L-cone-opic. Relating to the human L-cone response due to its photopigment and its characteristics in the context of ipRGC-influenced responses to light.⁴

Note 1: In this standard [CIE S 026/E:2018], L-cone-opic is based on the cone fundamental, as defined in the CIE Fundamental Chromaticity Diagram.⁵ This differs from the approach where the human L-cone response is denoted by the term *erythropic* and its spectral sensitivity function is based on an opsin template.^{6,7}

Note 2: The subscript *lc* is used to indicate L-cone-opic quantities.

rhodopic. Relating to the human rod cell response due to its photopigment (rhodopsin) and its characteristics in the context of ipRGC-influenced responses to light.⁴

Note 1: In this standard [CIE S 026/E:2018], rhodopic is based on the sensitivity function for scotopic vision, $V'(\lambda)$, as defined in (ISO 23539/ CIE S 010). This differs from the approach where the human rod cell response is also denoted by the term *rhodopic* but its spectral sensitivity function is based on an opsin template.^{6,7}

Note 2: The subscript *rh* is used to indicate rhodopic quantities.

melanopic. Relating to the human ipRGC response due to its photopigment (melanopsin) and its characteristics in the context of ipRGC-influenced responses to light.⁴

Note 1: For the melanopic action spectrum $S_{mel}(\lambda)$, this standard [CIE S 026/E:2018] uses the shape of the opsin-template-based melanopic spectral sensitivity function $N_z(\lambda)$.^{6,7}

Note 2: The subscript *mel* is used to indicate melanopic quantities.

blue-appearing light. (See subheading under *light*.)

broadband light. (See subheading under *light*.)

chronotype. A person's natural inclination with regard to the times of day when they prefer to sleep or when they are most alert or energetic. This preference can be driven by the timing of the internal 24-hour circadian clock, the rate of build-up and decline of homeostatic sleep pressure (sleepiness) due to the duration of time awake or time asleep, or in practice, a combination of both.⁸

dose. In this document: A quantity of light exposure taken, or recommended to be taken, at a particular time or over a specified period for eliciting a physiological or behavioral effect. In some cases, the quantity is determined by spectrally weighting the radiant exposure by the appropriate action spectrum for the intended effect.

dosimeter. A device used to measure an absorbed dose of ionizing or non-ionizing radiation.

entrainment. The process of activating or providing a timing cue for a biological rhythm. Examples of entraining cues are light and meal timing.³

integrative lighting. Lighting specifically integrating both visual and physiological effects, and producing physiological and/or psychological benefits for humans.¹⁸⁷

Note 1: The term *integrative lighting* applies only to humans.

Note 2: Lighting used primarily for therapeutic purposes (i.e., light therapy) is not included.

Note 3: The term *human centric lighting* is sometimes used with a similar meaning.

intrinsically photosensitive retinal ganglion cells (ipRGCs). Retinal ganglion cells that are photosensitive by means of the photopigment melanopsin.⁴

Note 1: The ipRGCs receive signals from rods and cones and hence combine the photoreceptive contributions from all five α -opic photopigments. Melanopsin, however, is the only known photopig-

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ment that occurs within the ipRGCs themselves, thus accounting for the intrinsic photosensitivity of the ipRGCs.

Note 2: The ipRGCs are occasionally denoted as photosensitive retinal ganglion cells, or melanopsin-expressing retinal ganglion cells, or melanopsin-containing retinal ganglion cells.

ipRGC-influenced responses to light. Light-induced physiological and behavioral responses or effects that can be elicited by stimulation of ipRGCs.⁴

Note 1: The ipRGCs are known to play a role in both visual and physiological responses to ocular light exposure. In the past, ipRGC-influenced responses to light were often referred to as non-image-forming (NIF) or nonvisual (NV) responses, to reflect their distinction from perceptual vision. This standard recognizes these distinctions while allowing for the possibility for the accepted range of ipRGC-influenced responses to light to expand as more knowledge is gained.

Note 2: The ipRGC-influenced responses to light may also be influenced by rod, cone, and melanopsin inputs, depending on the duration and irradiance of the light exposure.

L-cone-opic. (See subheading under *alpha-opic*.)

light. Radiant energy that is capable of exciting the retina and producing a visual sensation in humans. The visible portion of the electromagnetic spectrum extends from about 380 nm to about 780 nanometers (nm).²

broadband light. In this document: Visible electromagnetic radiation with a spectral power distribution with: 1) several peaks; or 2) particular wavelengths emphasized against a background of white electrical light or daylight. Such a light source could also be characterized as polychromatic.^{9,10,11,12}

narrowband light. In this document: Visible electromagnetic radiation with a spectral power distribution that has a single peak with a half-peak bandwidth in the range of 15 to 90 nm, within one color appearance range.^{10,13,14}

monochromatic light. In photobiology, monochromatic light has a half-peak bandwidth of 15 nanometers or less.^{9,10} The scientific literature

in this RP predominantly follows the principles of photobiology.

In physics, monochromatic radiation is characterized by a single frequency or a single wavelength.¹⁵

Note 1: If the wavelength is used to characterize a monochromatic radiation, the medium has to be stated.

Note 2: In practice, monochromatic radiation is radiation of a very small range of frequencies or wavelengths, which can be described by stating a single frequency or wavelength.

blue-appearing light. Optical radiation between approximately 440 and 490 nm (2.82 to 2.53 electron volts [eV]).^{16,17}

red-appearing light. Red-appearing light is optical radiation between approximately 610 and 780 nm (2.03-1.59 eV).^{16,17}

polychromatic light. In this document: Visible electromagnetic radiation with a spectral power distribution that spans more than one color-appearance domain. Such a spectral power distribution can: 1) span the entire visible range of 380 to 780 nm; 2) have multiple peaks across the 380- to 780-nm range; or 3) be a single peak that has a half-peak bandwidth of more than 15 nm and crosses two or more color-appearance ranges.^{9,10,11,18}

M-cone opic. (See subheading under *alpha-opic*.)

melanopic. (See subheading under *alpha-opic*.)

melanopsin. An opsin-like protein, sensitive to light, with a peak sensitivity around 490 nm,⁷ and found in the very small proportion of human retinal ganglion cells that are directly photosensitive.¹⁹

melatonin. An amine hormone, produced mainly by the pineal gland as a metabolic product of the neurotransmitter serotonin. Melatonin is the biochemical signal of darkness and helps to regulate circadian and circannual changes in physiology. It is implicated in the initiation of sleep and in the regulation of the sleep-wake cycle.³

monochromatic light. (See subheading under *light*.)

narrowband light. (See subheading under *light*.)

neurobehavioral. (See subheading under *physiological responses to light*.)

neuroendocrine. (See subheading under *physiological responses to light*.)

objective. (See subheading under *physiological responses to light*.)

opsin. Opsins are light-sensitive protein-coupled receptors found in photoreceptor cells of the retina.

physiological responses to light:

acute responses. Direct neuroendocrine or neurobehavioral responses to light that do not require involvement of the circadian clock, even if those light signals can be transduced via the suprachiasmatic nuclei (SCN). An example of this is acute light-induced suppression of melatonin during the night.

neurobehavioral responses. Those having to do with the way the brain affects simple behaviors, or complex behaviors such as cognitive performance, emotions, and learning.²⁰

neuroendocrine responses. Those having to do with the interactions between the nervous system and the endocrine system. The endocrine system comprises glands that create and secrete hormones which are chemicals that coordinate different functions in the human body. Neuroendocrine cells release hormones or trophic factors into the blood or surrounding tissues in response to stimulation of the nervous system.²⁰

objective responses. Those having verifiable existence in the external world, independently of any opinion or judgment,³ for example, cognitive performance tests.

subjective responses. 1) Those taking place or existing only within the mind. 2) Those particular to a specific person and thus intrinsically inaccessible to the experience or observation of others,³ for example, subjective sleepiness ratings.

polychromatic light. (See subheading under *light*.)

red-appearing light. (See subheading under *light*.)

rhodopic. (See subheading under *alpha-opic*.)

S-cone-opic. (See subheading under *alpha-opic*.)

subjective. (See subheading under *physiological responses to light*.)

3.0 Circadian, Neuroendocrine and Neurobehavioral Responses to Light

3.1 Light Detection at the Eye

Light reaching the retina is converted to neural signals by at least five types of cells, collectively called photoreceptors. These photoreceptors provide the input for vision and for many behavioral and physiological responses, some of them direct and others mediated by influence on hormone secretion. **Annex B – Scientific Background** and IES TM-18-18¹ provide detail concerning the scientific foundations of how these cells detect light and the effects of this light exposure.

Each photoreceptor has a characteristic spectral sensitivity function and characteristic operating range. Rods are responsible for photoreception at relatively low light levels (scotopic vision occurs below approximately 0.001 candela per square meter [cd/m^2]) and saturate at higher light levels; the long-, medium-, and short-wavelength cones provide the basis of color vision but require a higher light level for true photopic vision (above approximately 5 cd/m^2). The intrinsically photosensitive retinal ganglion cells (ipRGCs) detect light primarily for functions other than vision, although they also play supporting roles in vision. Stimulation from the ipRGCs resets the circadian (24-hour) body clock, directly influences the secretion of certain hormones, and increases alertness during both day and night. All of the photoreceptor types also interconnect in complex ways that are the focus of current research attention; for instance, it is becoming clearer that there are interconnections between cells responsible for vision and the ipRGCs.

CIE standard S 026:2018⁴ expresses the international consensus concerning the spectral response of these

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five cell types. **Figure 3-1** shows the action spectra for the five known photoreceptors.

Of greatest interest for this document is the spectral response curve for the ipRGCs, known as the melanopic spectral response curve. The curve was developed primarily (though not only) from data showing that light at night acutely suppresses secretion of the hormone melatonin,^{6,21,22} with a peak in the short-wavelength range. When this work was originally performed, it was thought that the ipRGCs played no role in visual responses and that the effects of this light exposure were principally the regulation of circadian rhythms. For these reasons, the phrases “nonvisual effects,” “non-image-forming effects,” “circadian effects,” and “circadian light” came into common usage. It is evident that there are interconnections between the various photoreceptors and that the effects of light exposure beyond vision are more varied than just circadian regulation. Therefore, it is incorrect to use any of these former phrases to describe the phenomena

that are the focus of this document. The International Commission on Illumination (CIE) has proposed a term to describe effects of light on humans that involve the five parameters that influence these effects.

The study of these effects is a very active area of neuroscience, photobiology, and applied architectural lighting, with dozens of new scientific publications each year. The recommendations here will evolve as knowledge accumulates. For example, it is now known that there are at least five different subtypes of ipRGCs,^{23,24,25} but how they combine to influence any of the outcomes discussed below is not known, nor is it clear whether there are variations in their action spectra. The remainder of this section briefly summarizes the state of knowledge in 2020, with a focus on studies involving adults active during daytime. Further details concerning the scientific background are available in **Annex B – Scientific Background**.

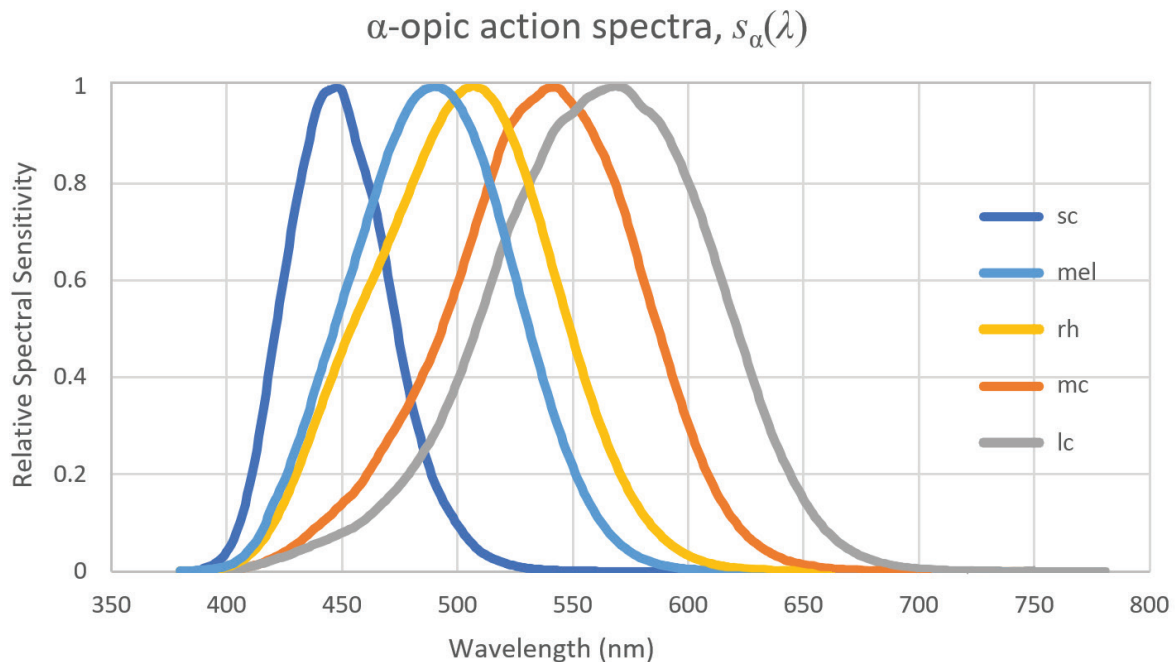


Figure 3-1. The action spectra for the five known α -opic photoreceptors (rods labeled rh; short-, medium-, and long-wavelength cones labeled sc, mc, and lc; ipRGCs labeled mel). (Graphic adapted by Benjamin Warfield from the graphic sources provided courtesy of the CIE: Figure 2 in Workshop report from the Proceedings of the 29th Session of the International Commission on Illumination (CIE) and Figure 1 in CIE S 026/E:2018 CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light)

3.2 Circadian Regulation

There is no question that the ipRGCs provide the circadian clock with environmental information about light and dark,²⁶ and that these daily signals are the principal means by which, under normal circumstances, circadian rhythms are synchronized with day and night.²⁷ Knowledge concerning the spectral sensitivity of the human ipRGCs comes extensively from the effects of exposure to light in narrow wavelength bands on nighttime melatonin secretion, alertness, and circadian phase shifting.^{6,14,21,22,128,129,130,133,134} What is less well established is how exposure to polychromatic white light—as is used in general illumination—sets circadian phase.²⁸ Studying this question is particularly challenging because studies of circadian phase-setting (as compared to melatonin suppression studies) require greater control of numerous experimental factors.

What is known is that the timing of light exposure determines whether that exposure phase-shifts the clock to earlier times (phase advances) or to later times (phase delays). Under normal conditions, light exposure in the late evening will delay the circadian system to a later phase, and light in the early morning will advance the circadian system to an earlier phase.²⁷ Although increasingly intense exposures have a stronger effect, the relationship is not linear.²⁹ The relationship is also not linear for the exposure duration: shorter light exposures are more effective per minute.^{30,31} Similarly, intermittent (as opposed to continuous) exposure induces a greater phase shift than predicted by a simple linear response to light duration.^{32,33}

There is also evidence that the sensitivity of the circadian system to light might be determined by prior light exposure over the previous hours and possibly days,^{34,35,36} with increased prior exposure to light “desensitizing” the system and causing a modest reduction in the magnitude of the subsequent response to light. While these principles are established, their utility for improving light for general daytime functioning is not yet known.

3.3 Daytime Acute Responses to Light Exposure

This section focuses on physiological responses that do not involve the circadian clock, which are called *acute*

responses. Some of these responses manifest immediately, during the light exposure (e.g., some effects on cognitive performance); others become evident after a longer time delay (e.g., subsequent sleep quality).

There is strong agreement that five parameters influence circadian, neuroendocrine, and neurobehavioral responses: the spectrum, quantity, duration, timing, and pattern of exposure of the light.³⁷ The first two parameters relate to the quantity of light exposure through the spectral response function, with duration contributing to the total dose received. The timing and pattern of exposure relate to the sensitivity of the body to this exposure, which changes depending on the state of other physiological processes, including the sleep-wake cycle.³⁸ This short review addresses light exposures during daytime hours among people who are active by day. (For greater detail on the acute alerting effects of light, refer to reviews.^{39,40,41,42}) Furthermore, the emphasis here is on responses to polychromatic, white-appearing light, such as is used for general illumination. There is considerable disagreement concerning how to apply research results from studies with light in a narrow range of wavelengths (which appears colored) to general lighting; these issues are discussed in **Annex B – Scientific Background**.

3.3.1 Immediate Responses. Immediately after being exposed to an increase in light level, pupil size decreases in response to signals from rods and/or cones. If the exposure is sustained and the level is high enough, then signals from the ipRGCs maintain this pupil size.⁶ This is one example of interconnection between what had been thought of as the visual system (rods and cones) and the ipRGCs. For example, Lucas and colleagues used the time-dependent change in the neural signals responsible for pupil size to illustrate the complexity of retinal responses to light exposure, which continue to be the focus of research attention.¹⁰³

The immediate effects of light exposure during daytime hours on other physiological indicators remain under debate. Exposure to white light at night immediately suppresses the release of the hormone melatonin and increases alertness,⁴² effects that underpin the identification of the ipRGCs and of the action spectrum for melanopsin, the active photoreceptor molecule. This

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has led many to think that exposure to white light by day must also have similar immediate alerting effects. The general hypothesis has been that by increasing the intensity of ipRGC exposure, either by increasing the light level at a fixed spectrum, or by manipulating the light source spectrum to specifically target the melanopic action spectrum, one can increase daytime alertness. The resulting studies are described below.

Lok and colleagues reviewed the literature concerning the effects of white light exposure at night or by day on physiological and self-reported measures of alertness.⁴⁰ The physiological measures that appeared in the literature included central nervous activity (measured using electro-encephalography [EEG]) and autonomic nervous activity measures, encompassing skin temperature, core body temperature, heart rate, and heart rate variability. Of the 11 studies that had examined the effects of light exposure intensity (each of which increased light level without changing spectrum) on these outcomes, four found null effects, one found ambiguous results, three found results that also depended on other variables, including time of day and the duration of exposure, two found positive results (higher light intensity leading to physiological evidence of increased alertness), and one found a negative result. Noting that the experiments varied in research design, the degree of experimental control (e.g., not all studies had controlled for prior light history), and in the choice of physiological measures, Lok and colleagues concluded that the field would benefit from a more systematic approach to these experiments, with a directed focus on identifying dose-response relationships.

3.3.2 Cumulative Responses. Two important categories of physiological responses develop over longer time exposures: self-reported subjective responses and task performance effects. Qualitative review papers have recently summarized the state of the science for both sets of outcomes.

Lok and colleagues included both performance and self-reported indicators of daytime alertness in their review of the effects of light exposure studies.⁴⁰ The task performance outcomes included measures that indicate alerting attention (e.g., vigilance tasks that require a response to every stimulus) and those involving control

over executive function (e.g., tasks that involve cognitive inhibition, such as distinguishing between targets and non-targets). As noted in **Section 3.3.1 Immediate Responses**, the studies reviewed had manipulated light exposure by increasing white light levels. Of 17 studies that had included performance measures, only three found consistent evidence that higher light exposure caused better performance on these tasks, which would be interpreted as increased alertness. The remainder found either null or inconsistent results. Souman and colleagues also reviewed this literature and reached the same conclusion,⁴¹ having found that of 12 studies including performance outcomes in relation to morning or afternoon light exposures, only two showed evidence of increased alertness resulting from increased daytime light exposure. Both review teams concluded that research design limitations, including poor or insufficiently systematic choices of light levels for comparison and small sample sizes, have reduced the quality of the evidence.

Measures of self-reported alertness include various scale ratings, often using the Karolinska Sleepiness Scale but sometimes using other questionnaires or combinations of questions. Lok and colleagues found⁴⁰ that the studies they reviewed most consistently reported that higher light exposures led to stronger self-reports of alertness (or lower subjective sleepiness) in 14 of the 18 studies in this category. Four of the studies, however, found null results. Similarly, Souman and colleagues⁴¹ identified 25 studies involving tests of the effects of daytime light levels on self-reported alertness, of which 17 showed positive results. There is not yet a clear dose-response function established. Souman and colleagues noted that even for self-reported alertness, the results for experiments in which exposure durations were varied did not show stronger effects on self-reported alertness, even though one would expect a larger dose to have been delivered. Lok and colleagues noted⁴⁰ that it is nearly impossible to rule out a placebo effect for the self-reported alertness outcomes because, in general, participants are aware of the experimental manipulation.

If the physiology for any effects of light exposure on daytime alertness involves the ipRGCs, then it should be the case that increasing the melanopic illuminance by changing the light source spectrum, ideally while holding phot-

opic illuminance constant, will increase alertness. One review of the literature on nighttime effects found that calculating the exposure using melanopic illuminance provided a better prediction of self-reported alertness than did photopic illuminance.⁴¹

Souman and colleagues also reviewed these effects for daytime exposures.⁴¹ Very few of the investigations that passed their rigorous quality filter included daytime light exposures. Three studies included comparisons of daytime exposures to light of varying spectral content and measures of self-reported alertness, and only two included performance measures of self-reported alertness. None of these investigations showed positive effects (i.e., that increased exposure to short-wavelength radiation improved alertness).

Whereas both Souman and colleagues⁴¹ and Lok and colleagues⁴⁰ focused on laboratory experiments, Pachito and colleagues reviewed⁴³ the literature on the effects of light exposure on alertness and mood in daytime workers in real workplaces. Their review was performed for the most rigorous source of scientific literature reviews in health and medicine, the Cochrane Reviews. They first identified 2,844 possible references for inclusion, but applying the stringent Cochrane criteria resulted in only five papers remaining. The authors graded the quality of the evidence on this topic as very low, but did conclude that there is some evidence that light of a correlated color temperature (CCT) greater than 5000 K might increase alertness, but not improve mood, among daytime workers. They further noted that small sample sizes, the possibility of bias in the data, and poor reporting of research method details reduced their assessments of the level of evidence.

3.3.3 Delayed Responses. In 2004, the CIE concluded, based on the literature to that time, that people who receive a higher daily light dose experience better overall well-being than those who receive a relatively low light dose. The organization updated this statement in 2009.⁴⁴ The evidence for this comes from investigations into the effects of light exposure on responses that either occur after the exposure itself (e.g., self-reported sleep quality) or are integrated over many hours or days (e.g., self-reports of feelings of vitality or mood). There is no clarity in these findings that the effects stem from

effects on circadian regulation, although there may be a role for circadian processes.

In this domain fall the increasing number of field investigations in which individuals are equipped with light-monitoring dosimeters for a few days, and in parallel they report their experiences. Some studies use daily sleep diaries with daily questionnaires; others add intermittent questionnaires throughout the days and evenings of the light monitoring. For example, one team⁴⁵ equipped participants with light monitors and asked them to complete a paper questionnaire after each social interaction; the paper questionnaires were mailed back to the research team. The social interactions made after periods of very high light exposure (more than 1,000 lx on a wrist-worn monitor) were rated as more agreeable and less quarrelsome. Studies like this one indicate that higher light doses might be desirable, but there are many questions about the quality of the light measurement, the absence of spectral data for the light exposures, and the fact that people were in many different settings, all of which make it very difficult to develop actionable design recommendations from such studies.

Nonetheless, there is a growing literature to confirm that daily light exposure influences well-being. Boubekri and colleagues⁴⁶ assessed sleep quality and overall well-being and measured sleep duration among office workers whose workplaces were either windowless or near a window. Daily light exposure on workdays was higher for those near windows, and those individuals had longer sleep duration, better sleep quality, and higher feelings of vitality. Similarly, Figueiro and colleagues⁴⁷ monitored light exposure among occupants of five buildings in four cities across the United States, for seven-day periods in both summer and winter; at the end of each light monitoring period, the participants completed questionnaires concerning depressive symptoms, mood, feelings of stress, and sleep. People receiving higher light exposure over the whole workday reported better sleep quality and mood.

Hubalek, Brink, and Schierz⁴⁸ monitored total white-light exposure and exposure in the short-wavelength region, and found that people who had received greater white-light exposure during the day reported better sleep quality the following night. This effect was not

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associated with greater short-wavelength exposure, probably because the magnitude of the light level differences far outweighed any spectral effects.

A better indicator of the possible role for spectral effects on subsequent nighttime sleep comes from a field experiment using two fluorescent lamp types.⁴⁹ One light source had been designed to have a greater short-wavelength component than the other, with both having similar emissions in the mid- and long-wavelength ranges. The experimental lamp delivered a lower photopic illuminance but a higher melanopic illuminance to the workplace (although daylight was also present and accounted for approximately 30% of all light exposure). When the experimental lamp was installed, office workers reported better nighttime sleep. A caveat to this finding is that Pachito and colleagues⁴³ rated the quality of this evidence as very low in their review, because of potential biases in this field study.

The data from Figueiro and colleagues⁴⁷ also showed that the time of day of the light exposure and the season affected the responses. Participants with higher light exposures in the morning fell asleep faster that night and had better sleep quality than those with lower light exposures in the morning. This conclusion was echoed in the review of the effects of light on sleep by Dautovich and colleagues (2019),⁵⁰ which included both experimental and field monitoring studies of community-dwelling adults, but which did not include the paper by Figueiro and colleagues. Bright morning light was associated with better and earlier sleep the following night.

The precise physiology underlying the effects of light on mood, cognition, and sleep remain unknown, but it appears that multiple pathways might be involved.^{47,51,52} Figueiro and colleagues⁴⁷ provided evidence of this complexity by examining activity rhythms in addition to the sleep quality and mood outcomes discussed above. All of the reviews in this field have noted that it can be very difficult to control for all of the interconnected processes because the responses measured will be a blend of immediate responses and influences on circadian regulation. Fisk and colleagues cautioned⁵¹ that too few investigators have fully taken these varied effects into account. When considering the overall effects of daily light exposure on human health and well-being, it is important to

note that there is huge variability in the pattern of light exposures over time and between individuals, in intensity, spectral content, and spatial distribution. One team has described this variability as a “spectral diet.”⁵³ Using average illuminance measures alone to characterize daily light exposure is analogous to knowing the individual's total caloric intake without knowing the combination of nutrients that contribute to that total. Webler and colleagues suggested that the availability of small, wearable sensors combined with mathematical modelling of the resulting data could lead to advances in understanding how daily light patterns support, or do not support, circadian regulation and other outcomes.⁵³

3.4 Summary of Human Physiological and Behavioral Responses to Light

Human physiology and behavior are beautifully complex. The small army of scientists studying the effects of light exposure on humans has known of the existence of ipRGCs for barely two decades. It has become clear that the daily pattern of light and dark exposure is the most important signal for circadian regulation. A strong day-night signal, with time every day spent in darkness, is necessary for health.⁴⁷ A substantial body of research^{54,55} into the effects of light exposure at night (when the brain expects to be asleep and in darkness) lies outside the scope of this RP for daytime lighting.

There is good agreement, based on literature up to June 2020, that during the day, a higher light exposure will contribute to a good night's sleep, provided that one also avoids bright light exposure in the hours leading up to bedtime.²¹³ Averaged over time, this pattern of higher light exposure is also associated with better mood and feelings of well-being. The extent to which these effects are linked to the ipRGCs, apart from circadian regulation, is not clear.

There is mixed evidence that daytime light exposures directly affect alertness. Alertness can be measured with physiological indicators, performance indicators, and self-report measures. The most consistent results are for self-reported, subjective alertness.^{42,215} Experimental investigations tend to find that changes in photopic illuminance can produce changes in self-reported alertness, whereas changes in light source spectrum are less consistent in their effects. The Cochrane Review of

field investigations, however, found some evidence that light sources with higher short-wavelength content can improve daytime alertness.⁴³

Among the reasons for the inconsistent results are the differences in experimental methods noted in **Section 3.3 Daytime Acute Responses to Light Exposure** and its subsections. Many investigations have included smaller sample sizes than are needed to detect quite subtle effects.^{40,41,43} Some studies have included “low” light levels that might have been above the threshold for responding.⁴⁰ Among the most challenging problems is the tendency for many researchers to characterize the light sources only in terms of CCT, perhaps without realizing that for any given CCT there can be an infinite number of very different light source spectra, and these will vary in the stimulus each provides to the various photoreceptors. Souman and colleagues demonstrated⁵⁶ the potential to use spectral tuning to hold CCT and photopic illuminance constant while considerably varying the melanopic illuminance, with the result that melatonin suppression during nighttime exposure to these light sources aligned with the spectral sensitivity of melanopsin.

There are several ways to change the light exposure: increase the light quantity (deliver more energy, whatever the spectrum), or target the spectrum to deliver energy in the wavelength range closest to the spectral sensitivity of the photoreceptor that is believed to be most responsible for the effect in question. The value of targeting the spectrum lies in the potential to give a stronger stimulus with less energy. Of course, for practical purposes there are limits to this approach; other application considerations, including visual performance and color rendering, will also influence both light level and light source spectrum choices.

4.0 Measurement of Light for Physiological Responses

To gather and share data on the physiological effects of light on human health, it is important

for lighting application specialists and scientists to have common vocabularies and to communicate the parameters relevant to the circadian, neuroendocrine, and neurobehavioral responses in humans. Different levels of measurement and reporting rigor are required for different levels of lighting applications or studies. The intent of this section is to articulate the important principles and parameters needed for clear documentation and communication. It is important to note that designing lighting to foster human health and well-being is a nascent field. This work draws from published biomedical research, but the majority of that information is developed under carefully controlled laboratory conditions. People live, work, and play in environments that are quite different from controlled laboratories. Hence, professionals who specify and design lighting have the important opportunity to contribute to the developing field of light and human health by providing relevant lighting measures of their projects for use by their peers and the broader scientific community.

The principles include the following:

- Measure, or design for, light levels delivered at the plane of the individual's eye and in the direction of gaze, not on a horizontal task plane.
- Use correct International System of Units (SI) quantities to describe light exposures.

Conventional metrology for lighting uses the photopic spectral luminous efficiency function, $V(\lambda)$, which peaks at 555 nm, to predict visual function. The resulting photopic luminance (cd/m^2) and photopic illuminance (lx), however, are not the correct quantities to use when considering biological or behavioral responses to light. At present, it is recommended to consider a set of five quantities (one for each of the unique spectral luminous efficiency functions of the known photoreceptors) to characterize light exposures.

4.1 Light Spectrum

The international standard that establishes the photometric and radiometric quantities and units related to light received at the eye is *CIE S 026/E:2018, CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light*.⁴ This standard describes the weighting functions (action spectra) for the five

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known types of photoreceptors: rods, three types of cones, and the melanopic ipRGCs. **Figure 3-1** shows the action spectra for the five known α -opic photoreceptors. One would take the spectral power distribution of a given light source, or the spectral power distribution of lighting conditions measured in the field (vertically, at the location of the viewer's eye), apply the appropriate spectral efficiency function, and calculate the desired quantity. One could also use the spectral luminous efficiency function, $V(\lambda)$, to calculate illuminance in the familiar way, for comparison to the chosen α -opic equivalent illuminance (e.g., melanopic equivalent illuminance). The use of this international standard ensures that the calculated quantities may be compared directly.

In sighted individuals, strong evidence shows that the melanopsin ipRGCs are functionally and anatomically interconnected with the rods and cones that support vision; therefore, the input from the ipRGCs alone is insufficient to completely describe physiological effects. The relative importance of each photoreceptor type changes depending on context, which is why there is no single metric that can be applied for all situations.

An independent analysis of data from multiple laboratories has shown that the value of melanopic Equivalent Daylight Illuminance (melanopic EDI) is the most accurate and best available predictor for circadian, neuroendocrine, and neurobehavioral responses in humans.⁵⁷ This is discussed further in the subsections below. Melanopic EDI is currently a sufficient and recommended metric for daytime interior environments.^{4,57}

To calculate any of these quantities requires measurement of the spectral power distribution (SPD) of the light received at the eye, from 380 nm to 780 nm. Fortunately, commercially available spectroradiometers and spectrometers have achieved price points that are relatively accessible to the lighting community. If the meter utilized does not automatically calculate the desired quantity, measurement of the SPD should be performed in increments of no more than 5 nm. Ideally, the incident light at the eye is measured with a spectroradiometer in situ. If a spectroradiometer or

spectrometer is not available SPD data provided by the lighting manufacturer may be used, combined with irradiances or illuminances measured with an instrument at the plane of the eye. Directly measured SPDs, however, are preferable to reliance on data from manufacturers, since SPDs may vary from one product generation to another and because the finishes in a room affect the spectral content of light reaching the eye. A toolbox⁵⁸ is provided to facilitate the correct calculation of quantities that describe the exposure that a given photoreceptor type receives from a given light source spectrum. Guidance on more detailed measurements required for research purposes is provided in CIE TN 011:2020⁵⁹.

Studies employing more rigor may require reporting of the spatial distribution of the radiances in the visual field, duration of light exposure, time of day of light exposure relative to an individual's own circadian cycle, light history of the individual, and characteristics of the individual that could affect their response to light and dark.

4.2 Practical Measurement

Illuminance and spectral content shall be measured at the level of the eye of the individual, orthogonal to the plane of the eye (i.e., in the vertical plane), in a given direction and at a given height and distance from the light source or wall. Additional measures in other known directions at regular intervals or in a grid across a space might be useful to define the environment objectively, without interpretation of gaze behavior of the individual. For example: four measurements, each in a vertical plane 90 degrees apart and at the height of the eye (about 1.2 m, or 48 in., above the floor), with one additional measurement at 1.6 m (standing) or 1.2 m (sitting) in the horizontal plane to measure maximal exposure (see **Figure 4-2**). The time of the exposure to the light source (time of day and day of the year) and weather conditions (if daylight is available) should be recorded. While it is difficult to reliably assess actual light exposure at the cornea given head and eye movements, the individual's "direction of view" may be recorded, and head and eye movements could be documented and factored into a calculation of average realistic light exposure at the eye.

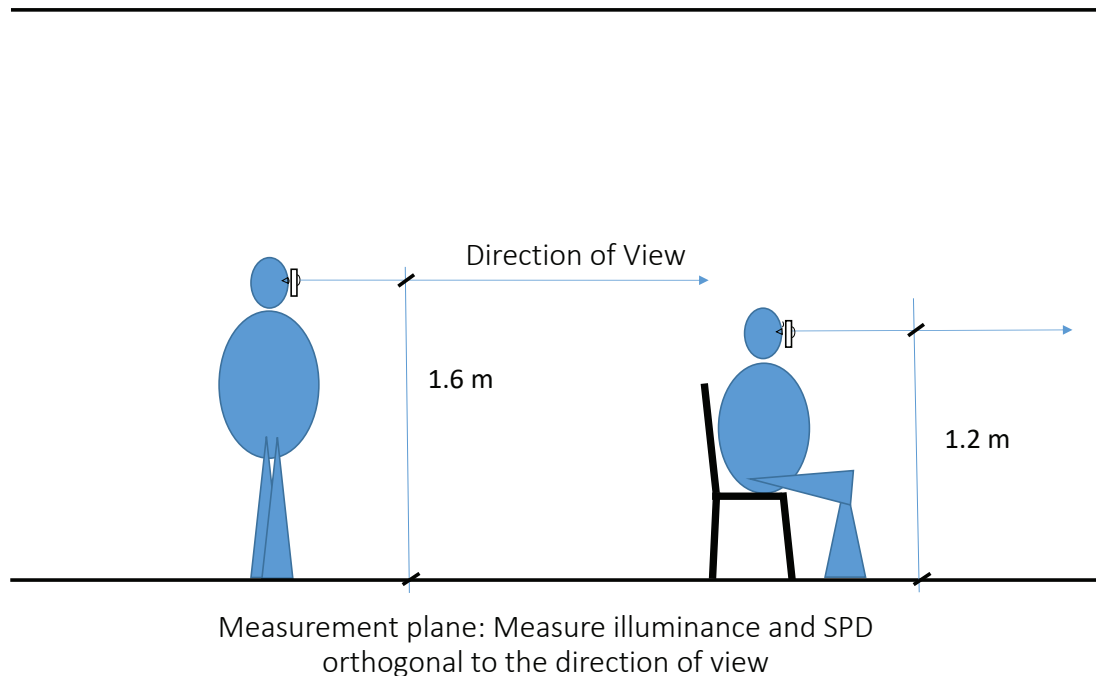


Figure 4-2. Examples of measurement positions relative to potential observer positions (not to scale).
(Graphic courtesy of Naomi Miller, PNNL)

4.3 Photometry and Radiometry

When documenting light exposure, it is essential that the lighting data include an SPD of the light source under each condition presented (such as daytime and nighttime), and if there are multiple sources in a test space at any given point, a composite SPD can be collected at the eye of the individual with a spectrophotometer and downloaded into a data file. The data can then be loaded into the recent CIE S 026/E:2020 calculator tool,⁵⁸ where they are weighted by the five α -opic efficiency functions (s-cone-opic, m-cone-opic, l-cone-opic, rhodopic, and melanopic) to attain the respective α -opic equivalent daylight (D65) illuminance (EDI) values.

For a moderate level of precision, knowing the SPD of the luminaire, the photopic illuminance at the eye and the five specific radiant watts values, a constant ratio of specific photoreceptor radiant watts to photopic lumens can be created and used. From then on, as long as the SPD of the source does not change, a high quality illuminance (or irradiance) meter can be used to collect illuminance (or irradiance) at the eye. Those measured values then can be integrated with the SPD to calculate input to the photoreceptors.

For domestic living or working applications in which lighting is intended to benefit human health and well-being, it would be ideal to take spectrophotometer measurements at each light setting once the project is completed and again at a later time to ensure that the lighting products or controls have not drifted in their spectral delivery over time. For controlled lighting research studies, it is best practice to repeat the spectrophotometer measurements at consistent and documented locations representing the individual's eye level and cardinal direction of gaze of each light setting, at least at the beginning and end of the experiment. In some studies, it is useful to take such measurements throughout the data collection.

Use of this approach, however, loses the spectral absorbance information about the individual finishes in a space. These data can be resolved into both illuminance and irradiance with any desired weighting (e.g., melanopic irradiance, rhodopic irradiance).

For research work, all light-measurement equipment should be calibrated at least annually. For field measurements, the spectrophotometer should be compared with a calibrated spectrophotometer before

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the measurements, to ensure that the meter's variation is within 5% of the calibrated radiance values.

It is important to note that wearable instruments are available for collecting continuous readings of light exposure received by an individual, but these types of instruments may automatically weight spectral input using $V(\lambda)$ or a specific model of light stimuli related to circadian, neuroendocrine, or neurobehavioral regulation, rather than collecting raw irradiance at all wavelengths. These instruments can be useful for assessing dynamic light exposures of individuals before and during experiments. Currently, these devices are limited in that they will not provide the detailed SPDs for light exposures needed for calculation of ipRGC photoreception.

4.4 Lighting Equipment, Room Geometry and Finishes, and Individual Location

Whether documenting lighting used for case study information in architectural spaces or in research experiments, it is essential to report details about the type of luminaire and its light source. Photographs of the luminaire should be provided, as well as a specific manufacturer name and detailed catalog number, so that readers and other researchers can glean details if needed. Furthermore, given the speed with which product revisions are implemented by manufacturers, archiving a manufacturer's specification sheet at the time of design and construction is important. If the luminaire uses separate lamps (e.g., fluorescent, incandescent, or LED), the manufacturer's name and full catalog number of those should be documented as well (e.g., Philips F32T8/TL41 fluorescent lamps in two-lamp 2x4 recessed fluorescent troffer with K12 acrylic prismatic lens and generic electronic ballast, or Lithonia 2SP32-K12-GEB). Because the luminaire's optical media may filter some of the spectral emission from the lamp, SPD measurements should be collected as the light passes through the luminaire's optical media (lenses, for example), or as the light is incident on the eye of the individual.

The geometry of the lighting system relative to the individual's location and view should be documented. Scaled layouts of the room and luminaires, in plan and section, allow rapid understanding of the space. Also important are photographs of the space, documenting

finishes, windows, luminaire locations, and furnishings. Is the individual reading, looking down at a desktop, sleeping horizontally in bed with eyes closed, or sitting in a classroom facing the teacher, with head tilted so that the gaze is slightly above horizontal? Fish-eye photos from the eye of the individual, with the individual's normal direction of view, are effective communication tools for this type of documentation.

More-extensive information on documenting the physical and lighted environment in human factors research may be found in CIE TN 011:2020.⁵⁹ Section 3.1.1 of *CIE 218:2016, Research Roadmap for Healthful Interior Lighting Applications* addresses the stimulus specification.⁶⁰

5.0 Lighting to Enhance Circadian Entrainment, Alertness, and Performance in Daytime Environments

Lighting practitioners may need to understand how to apply the knowledge of how light affects physiological and behavioral responses. There are two straightforward principles:

- In spaces where individuals are not sleeping—for example, in a workplace such as an office, factory, control room, school, or college—lighting for daytime alertness and performance, and by extension, for productivity and safety, will be an important consideration. This first principle is addressed by this RP.
- In spaces where individuals will sleep—for example, at home or in a care facility, hospital, dormitory, or prison—the ability to change the light level, wavelength, and pattern of light from day to night may be needed. The daytime lighting would follow the same recommendations as for alertness. Following dusk, however, and for as long as possible before bedtime, the illuminance may need to be low, and the light itself low in short-wavelength content, to reduce the direct alerting

effect of light and its negative impact on sleep. This change in lighting condition can be achieved in many ways, from simple approaches (e.g., different lamp types in ceiling luminaires versus bedside or table lamps) to complex hardware and software (e.g., lamps that are programmed to change their spectrum and output according to time of day). The complexities of this type of design consideration—and the design options associated with them—will be addressed by updates to this RP and/or by other future publications.

When lighting practitioners are designing for daytime functioning, they are focused on efficiency. This includes the efficiency of the work being performed (are visual requirements met?), the efficiency of the energy consumed (is the energy as low as practical?), and the efficiency of application (is the space conducive to the goals, and is the lighting accomplishing more than the simply meeting the visual requirements?).

Leading scientists who have studied the neuroendocrine, neurobehavioral, and circadian effects of light brought their collective knowledge on quantifying light for these physiological effects to an independent workshop in Manchester, UK, in 2013.^{6,7} In the years following this meeting, through an international consensus process, the CIE issued CIE S 026/E:2018,⁴ which defines a system for metrology of optical radiation for light-induced responses that can be elicited by ipRGCs. The CIE has defined these as ipRGC-influenced light responses.

CIE S 026/E:2018, defines spectral sensitivity functions, quantities, and metrics to describe the ability of optical radiation to stimulate each of the five α -opic photoreceptor types that can contribute, via the melanopsin-containing ipRGCs, to neuroendocrine, neurobehavioral, and circadian effects of light in humans. The units of these α -opic quantities are compliant with the International System of Units (SI), to provide traceable measurements linked to international guidelines.⁶¹

As discussed earlier, describing light solely with photopic illuminance [based on $V(\lambda)$] is inappropriate for characterizing light that elicits neuroendocrine, neurobehavioral, and circadian effects. All five

human photoreceptor types can contribute to these responses.⁶ The relative contribution of each individual photoreceptor type can vary depending upon the specific response and upon light exposure properties such as quantity, spectrum, duration, and timing. Calculation and dissemination of all five α -opic values in research studies and lighting applications will provide a database for the development of a refined, future metric that is relevant to the physiological effects of light. In the meantime, it is currently recommended to use α -opic melanopic equivalent daylight (D65) illuminance (EDI) for specific lighting designs and applications in typical everyday life for people with a regular, day-active schedule. In strong support of this recommendation, a recent independent analysis of nineteen laboratory studies that measured neuroendocrine, neurobehavioral, and circadian effects under a wide range of light spectra, quantities, and durations concluded that melanopic EDI is the most accurate and best available single photoreceptor predictor for these responses.⁵⁷

5.1 General Principles for Lighting Recommendations for Daytime Functioning

Given that the presence of a non-rod, non-cone photoreceptor in the mammalian eye for physiological responses was established, for the most part, through studying the circadian effects of light, it is not surprising that “circadian” effects are often promulgated when applying lighting to enhance physiological benefits. True circadian effects of light are quite limited, however, and—with the exception of daily entrainment—only occur under specialized circumstances.

Circadian effects of light involve entrainment of the intrinsic circadian pacemaker to a particular light-dark cycle, typically 24 hours under normal circumstances, or resetting (or phase shifting) the timing of the biological clock. The entraining and resetting effects of light depend on the circadian phase of light exposure, with light shifting the clock either earlier (advance) or later (delay), depending on the timing relative to minimum core body temperature. These responses are characterized by a phase response curve (PRC), which describes the effect of light timing on the direction and magnitude of the shift, including for blue light.^{62,63,216} Under normal conditions, light from

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approximately 6 p.m. to 6 a.m. will generally delay the clock, and light exposure from about 6 a.m. to 6 p.m. will generally advance it. Other physiological effects of light, such as melatonin suppression or the direct alerting responses, are acute responses to light and do not require involvement of the circadian clock, even if those light signals can be transduced via the suprachiasmatic nuclei (SCN), the site of the circadian clock.⁶⁴

On average, the intrinsic circadian pacemaker—in sighted humans—is slightly longer than 24 hours (about 24.2 hours)¹⁹⁴ and therefore requires a daily phase advance to remain entrained to a 24-hour day. The range in the population is from 23.5 to 25.0 hours; therefore, individuals with a period less than 24 hours require a daily delay, and those with periods further from 24 hours require a greater daily shift than those with a period closer to 24 hours.⁶⁵ The clock will entrain to light delivered at any time of day when delivered at the same time each day. This resetting and re-entrainment of the clock underlies adaptation to a new time zone following trans-meridian travel or in the rare cases in which shift workers fully adapt to their nightshift.⁶⁶

5.1.1 The Mistaken Use of “Circadian” in the Physiological Effects Lexicon. Most electric lighting systems, particularly those delivered to support daytime visual tasks, are not invoking additional circadian benefits. It is typical for sighted individuals to be entrained to 24 hours, even under lighting conditions considered poor, such as in dimly lit offices and areas with degraded lighting systems. A very small number of sighted people do have non-24-hour sleep-wake rhythm disorder, but this is often associated with unusual light-dark exposure (not a lack of light exposure), psychiatric disorders, or unusual pathophysiology in light sensitivity or their circadian period.⁶⁷ There is no evidence for generally occurring non-entrainment of individuals living or working in environments with poor lighting conditions.¹⁸⁸

As a further illustration of the functional separation of the visual and melanopsin photoreceptors' circadian responses,⁶⁸ low daytime light levels, if followed by darkness at night, are sufficient to entrain the clock.⁷³ Furthermore, a majority of visually impaired people, with only minimal ability to distinguish light from dark, remain entrained to the 24-hour light-dark cycle.^{69,70}

Lighting interventions given in the daytime to individuals living under typical light-dark cycles are, likely, not causing circadian entrainment where none previously existed and are not inducing substantial circadian phase shifts.^{71,72} While the benefits of light on the robustness of the circadian oscillation (its amplitude) have been postulated, measurement of circadian amplitude in humans is difficult, and there are no published studies demonstrating the benefits of enhanced circadian amplitude. Reported benefits of daytime lighting on nighttime sleep also do not require a circadian hypothesis; they may (or may not) work via the acute alerting effects in the daytime, thus improving the homeostatic regulation of sleep at night¹⁸⁹ and/or improving the sensitivity of the circadian system to dim light or darkness at night, and thereby reducing the adverse alerting effects of light prior to sleep.¹³⁹

The recommendation to change the quantity or spectrum of light delivered during the day is often marketed as “improved circadian entrainment.” As described in the preceding paragraphs, there is limited evidence for this in humans. While sunlight may change spectrum during dawn and dusk, some of these changes may not translate to the retinas once transmitted through the eyelids, or may be above the saturation threshold of the “circadian” or other “nonvisual response” dose-response curves. Mammals are unique in that the circadian effects of light are transduced exclusively via the eyes; therefore, closing the eyes to sleep induces a light-dark cycle at the retinas (where the light is detected) even if the environmental light conditions are different. Opening the eyes induces an increase in light arriving at the retinas of several orders of magnitude, essentially a square-wave response. Many mammals may not be awake at dawn⁷³ and, therefore, would not see the transient change in the amount or spectrum of light associated with dawn.

During the daytime, the natural light environment (that is, the quality of light available outdoors that is the source of the daylighting contribution for the interior built environment) changes relatively very little in terms of irradiance (it is virtually always higher than the saturation point for the circadian system) or spectrum. Therefore, for individuals with access to daylight in, or from, an outdoor environment, there is no ecological

justification to change either electric light quantity or spectrum for circadian entrainment.

In summary, the physiological effects of light include circadian effects, but circadian effects are a limited subset of the entirety of physiological effects.

5.1.2 Designing for Circadian Response vs. Designing for Behavioral Effects. Referring more accurately to the role of light when describing the physiological benefits of light will lead to greater clarification of the use of light and may simplify the approach. Description of the circadian benefits of light should be limited to the specialized applications where entrainment to a new cycle is required (e.g., during space exploration⁸⁷), where a natural light-dark cycle is not present (e.g., in space travel, in Antarctica¹⁹⁰), where resetting of the circadian phase is indicated (e.g., in jetlag¹⁹¹ or shiftwork¹⁹²), or in specialized conditions where circadian phase disorder is treated in a clinical setting (e.g., delayed sleep-wake phase disorders¹⁹³). Creating stable and regular bright days and dark nights is a good general principle, through use of light quantity and spectrum to create biologically stimulating days (higher light levels) and light at night that is as biologically close to darkness as is possible (lower light levels) when considering the context of the lighting application. Using light to improve daytime functioning can more simply be accomplished via the acute alerting effects of light without implementing technologies hoping to invoke circadian effects (e.g., color tunable technologies^{43,56}). This simpler approach will reduce the complexity and cost of the proposed lighting interventions, and clarify the benefits of light.

5.1.3 Designing for Both Visual and Physiological Functions. Lighting for physiological effects is most often not the only goal for an architectural design project. Visual task visibility, visual comfort, color rendering, dimming characteristics, flexibility of light levels and lighted areas, reduced flicker, aesthetics, energy use, maintainability, code compliance, and many other issues need to be juggled at the same time to reach an optimal lighting solution.⁷⁴ This RP provides guidance on how to maximize that outcome and is designed for use in parallel with IES's existing, vision-based, application RPs. Lighting designers should continue to ensure that all designs provide sufficient light to meet

visual requirements, after which the impact of lighting for physiological responses is considered by using the process described within this RP. The goal of this RP is to provide an additional level of consideration—essentially choices of light spectrum, quantity, and duration—once visual standards have been met.

5.2 Lighting Design Considerations

Lighting design for physiological responses requires broader definitions of criteria than those to which the lighting designer is accustomed to documenting when designing for visual response. The physiological response considerations for the lighting designer are defined from the perspective of the limited number of parameters that can be controlled by the design professional.

5.2.1 Environment Assessment. Similar to the assessment of the environment relative to visual requirements, documenting the design assumptions relative to potential or desired physiological responses will direct the choices made by the design team and occupants.

Occupants sleeping, occupants awake: Noting the intention of people in the space to be asleep or to be awake will help the designer understand which references to consult. The scope of this RP is limited to daytime environments in which occupants intend to be awake.

Parameters of the built environment: The built environment, including room surface finishes, partitions, furnishings, and the availability and proximity of daylight, should be noted. Dimensions (length, width, height) of built features and partitions are as important as room attributes for absorption and reflectance, as all of these features will modify the amount and quality of the light that reaches the eye of an occupant.

Types of visual work: The type of visual work and the type of lighting that best supports that work should be identified. Multiple visual task types on both vertical and horizontal planes are common in a single space, such as viewing computer screens, reading colored printed material, sorting electronic components, or viewing faces. Understanding the type of visual work performed

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in the space will allow the designer to understand the baseline level of illuminance in the space that will be available at the eye of an occupant.

Attributes of occupant population: The populations of people who work in and use the space and what hours they are there should be noted. Age (affects the transmittance of the crystalline lens), height (affects the elevation of the individual's eye), hours of lighting system use, and sensory sensitivities will be factors that contribute to the design decisions that are made while the lighting design and lighting control solutions are specified.

Priority of alertness: It is important to understand the different populations using or occupying a space, and then to prioritize which of those populations need alertness support at various times of day. It is important to ensure that the alertness design for one group does not negatively affect the needs of the other groups. The scope of this RP is limited to daytime environments in which occupants intend to be awake.

5.2.2 Parameters the Designer Can Influence.

It is important for the designer to understand the parameters that they can influence because design decisions can support (or diminish) the controllable aspects of a space necessary to achieve the desired physiological responses. A lack of understanding can allow a project to progress beyond the point in the design process where such decisions are relatively easy to accommodate. For example, window sizes and orientations are more easily modified during schematic design. If the design progresses through substantial completion of construction documents, however, options for daylight control may be limited to the type of shading.

5.2.2.1 Illumination at the Eye. Indoors, physiological effects are largely influenced by daylight, at the occupant's eye, from windows and skylights, provided that direct and reflected glare are controlled. Daylight contribution is always prioritized, and the quantity and availability should be accounted for through the use of controls to most efficiently achieve the desired illuminance levels at the eye.

For electric light, the quantity and distribution of light emitted from luminaires is considered. When selecting luminaires to maximize effectiveness for the alerting effect, direct luminaires with some diffuse luminous areas, indirect luminaires that deliver light to broad areas of white ceilings, and wall-washing luminaires that deliver light to light-colored walls are good choices. This is because all of these luminaire types provide light at the eye (important for providing alerting effects both effectively and efficiently) in addition to light at the horizontal work plane (important for seeing).

After making fenestration selections to bring daylight into the space, and electric light specification to produce the appropriate illumination within the space, the final significant area of designer influence on the illumination received at the eye is the consideration of maintaining the spectral integrity of the light reflected throughout the space. Selection of flat, low-sheen (non-specular) finishes that balance spectral reflection and spectral absorption characteristics on the light is important, including light-colored floors, walls, and ceilings, as well as light-colored furnishings like desks, tables, and chairs. Highly reflective white desks, for example, may produce discomfort glare so choices that maintain spectral integrity of the light also need to be balanced with sensible solutions for occupant wellbeing. Directing finish selections may seem to infringe on the notion of aesthetic preference. Within every color palette, however, there are "good," "better," and "best" choices relative to maintaining the spectral integrity and illumination values of a design; lighting designers should assist their clients and design colleagues with these choices—just as they would for lighting system choices for visual performance and energy code requirements.

5.2.2.2 Spectrum of the Light Reaching the Eye.

Illuminance at the eye is one factor the designer can influence. Another is the quality of the light reaching the eye. Preserving the quality of the initial SPD of the light source is important. The originating SPDs within the space are modified by the reflectance and spectral properties of the room surfaces and objects, creating the resultant spectral content of the light delivered to the eye. Light originating from all source types—daylight, electric light, even firelight—is modified by

every lens, window, shading device, and reflecting surface as it progresses through the space. Controlling these will affect the SPD received at the eye, and the light level, essential for creating a desirable lit environment for occupants.

An example of how the SPD can be modified through reflectance is cool-colored light reflected from a warm-toned wood-paneled ceiling. The warm wood will absorb many of the short wavelengths originating from the luminaire. Depending on the finishes selected, the lighting designer may need to adjust the light levels and the spectral content of the source to achieve the desired outcome.

In all cases, it is beneficial for the lighting designer to obtain finish samples and to understand the impact of selected finish and source combinations through the use of mockups, lighting software that takes spectral reflectances into account, and measurements.

5.3 Calculating Physiological Effects

Calculation of the physiological effects of light in interior daytime environments is complicated. It is important to note that research into how the eye transduces signals and combines these signals for effects throughout the day is ongoing. The visual lighting metrics and technical considerations required to calculate—or estimate—the physiological effects are presented in the subsections that follow, to assist the lighting community in selecting the best approach for a project's specific needs.

5.3.1 Relevant Visual Lighting Metrics. There are several visual lighting metrics that can help the designer understand, calculate, and estimate the physiological effects of light. They are discussed in the subsections that follow.

5.3.1.1 Luminous Flux. Measured in lumens, the luminous flux of a light source is calculated by mathematically weighting a light source's radiant output across the visible spectrum with the photopic luminous efficiency function $V(\lambda)$. This efficiency function was derived experimentally and describes the human visual system's sensitivity to wavelengths that activate the L and M cones. The $V(\lambda)$ function peaks at 555 nm, which is nominally yellow-green. Thus, the human visual system

is more sensitive to greenish light than it is to red or blue light. That is, 1 radiant watt of green light will appear brighter than 1 radiant watt of red or blue light. (Note that watts here are not electrical watts, but units of radiant power). Additional information may be found in *ANSI/IES LS-2-20, Lighting Science: Concepts and Language of Lighting*.¹⁸⁵

5.3.1.2 Luminous Efficacy of Radiation (LER). Measured in lumens per watt, LER is a measure of how efficiently a light source converts radiant power (measured in watts) into luminous flux (measured in lumens). The LER of a light source is the ratio of the lumen output to the radiant power of the light source.

5.3.1.3 Melanopic Equivalent Daylight Illuminance (Melanopic EDI). The CIE has recently recommended a method for calculating the relative melanopic content of a light source.⁴ The reference SPD is the CIE standard daylight at 6500 K, or D65. Melanopic equivalent daylight illuminance describes the amount of biologically relevant illuminance at the eye, in other words, the amount of illuminance at the eye that is available to influence physiological responses through the intrinsically photoreceptive retinal ganglion cells. Melanopic EDI is the melanopic equivalent of photopic illuminance, measured in lux. Melanopic EDI can be derived using the freely available CIE Toolbox⁵⁸ and the measured spectral power distribution reaching occupants' eyes from the specific lighting in an interior daytime environment. If it is not feasible to measure SPD at occupants' eyes, an alternate, less accurate approach is described in **Section 4.3 Photometry and Radiometry**.

5.3.1.4 Melanopic Daylight Equivalency Ratio (Melanopic DER). To calculate melanopic Daylight Equivalency Ratio, the light-source SPD is multiplied by the melanopic function, then divided by the number of photopic lumens in the source, yielding the melanopic equivalent flux per lumen. Next, the reference D65 SPD is multiplied by the melanopic function, then divided by its photopic lumens, yielding the melanopic equivalent flux per lumen of D65.

The ratio of the light source melanopic flux per lumen to the D65 melanopic flux per lumen is the melanopic

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Daylight (D65) Equivalency Ratio, or melanopic DER. This result is a measure of the melanopic content of a light source relative to the melanopic content of the reference D65 daylight.

Melanopic DER is a convenient ratio because it can indicate the relative melanopic “strength” of a light source, or a lighted environment, for simulating nonvisual responses and can allow easy comparisons between lighting conditions for a given quantity of light (i.e., illuminance).

As with melanopic EDI, melanopic DER can be derived using the freely available CIE Toolbox⁵⁸ and the measured spectral power distribution reaching occupants’ eyes from the specific lighting in an interior daytime environment.

5.3.1.5 Spectral Effects From Room and Object Surfaces. Illuminance calculations assume flat spectral reflectances of surfaces and objects in lighting calculations. The *spectral* absorption characteristics of these surfaces, however, are also important when considering the physiological effects of light. This specificity of room and object attributes is required and shall be taken into account in any tool that is used to calculate the illuminance and spectrum received at the eye. Software tools are available to perform this calculation; they use surface spectral reflectance files and light source SPDs as input (refer to **Annex A – Metrics and Models** for additional information).

5.3.2 Safety and Technical Considerations.

5.3.2.1 Blue-Light Hazard. Photochemical injury (photomaculopathy) associated with wavelengths between 400 nm and 550 nm can occur to the retina of the normal eye from staring at very high intensity light sources such as the sun, welding arcs, or laser beams. Sources available through retail channels should comply with national and international limits on exposure to light, and emit light at levels much lower than the maximum the standards permit. The blue light hazard is therefore not of concern for typical lighting installations.^{75,214} The American Conference of Governmental Industrial Hygienists (ACGIH) and the International Commission on Non-Ionizing Radiation

Protection (ICNIRP) provide recommended exposure limits for light, as does *ANSI/IES RP-27-20, Recommended Practice: Photobiological Safety for Lighting Systems*,⁷⁶ and these recommendations have been largely unchanged in the past two decades.

National and international safety limits assume that outdoor environmental exposures to visible radiant energy, at levels much higher than fluorescent or LED lights produce, is normally not hazardous to the eye except in very unusual environments, such as snow fields, oceans, and deserts. White LEDs generally have a higher short-wavelength component than would a standard fluorescent lamp providing the same lumen output. Therefore, some concern has been expressed regarding the use of single-die high-CCT LED sources.⁷⁷ The same concern, however, is not expressed with respect to the use of multiple-die LEDs for general lighting, where there is no risk for blue-light hazard.⁷⁸ Production of white light by combining three or more LEDs (e.g., red, green, and blue) has a similar effect.

5.3.2.2 Hazards From Use of Sources With Augmented “Blue” Wavelengths. Some LED products are marketed for health applications and often describe themselves as having a “blue-rich” or “blue-enriched” spectrum. There is no established definition for either of these terms, but the implication is that they are engineered to emit a higher proportion of melanopic content, that is, more radiation in the ipRGC’s spectral sensitivity range. There appears to be no published evidence that exposure to these light sources results in more risk than that associated with more commonly used lamps.^{53,78} As with all light sources, they would have to be tested for compliance with national and international safety standards for non-ionizing radiation.

As with all technologies, there are concerns about misapplication—intentional or accidental—of high-CCT or higher melanopic content lighting products (for example, a child may be unaware of the dangers of placing a lit toy close to his or her eye for an extended period of time). The reasonable course of action for the design professional is to specify light source compliance with ACGIH and ICNIRP safety standards in the construction documents and indicate usages that are considered typical, standard applications.

5.3.2.3 Energy Efficiency. Heritage sources, such as incandescent, fluorescent, and HID, are being replaced with LED technologies for many life cycle benefits, including long life, minimum maintenance, good lumen maintenance, and energy efficiency. If fluorescent lights are replaced by LED systems, with only energy efficiency in mind, an opportunity to enhance alertness within the space may be missed. Given the long lifespan of LED sources, the changes made to lighting systems to incorporate these new technologies will likely persist. The incentives offered for these types of efficiency upgrades will only be available to a consumer once, at the initial upgrade from a heritage source to an LED. Once the LEDs are the existing source technology, an additional upgrade may not be easily justified based on energy savings. LED replacement systems, if carefully designed with physiological principles in mind at the outset, can deliver more than just energy savings. These systems may yield additional life cycle benefits including alertness, improved task performance, and productivity.

5.3.2.4 Glare. Increasing irradiance or illuminance at the eye comes at the possible cost of increasing glare for occupants of the space. Discomfort glare is made worse by light sources of higher luminance and/or of smaller luminous area emitting in the direction of the eye. Solid-state lighting brings a myriad of opportunities for form factors and SPDs, but if bare LEDs are exposed to direct view, they can be uncomfortably bright. If the practitioner is designing for higher irradiances or illuminances measured in the direction of gaze, the following measures should be taken to reduce the perceived glare:

- Choose luminaires with lenses, diffusers, waveguides, indirect optics, or similar technologies optically designed to spread the light from the source over a larger area, thereby reducing the maximum luminance and associated discomfort.
- Luminaires with high luminance variation across the luminaire aperture should be avoided, especially those with visible high-brightness LEDs.
- For a given target irradiance or illuminance at the eye, a larger number of lower-intensity luminaires can produce physiologically effective light in a workspace more comfortably than a small number of high-intensity products. For example, designing

with both fixed (hardwired) and portable (corded task and general ambient) luminaires increases the quantity of sources and enables intensity reduction for each individual luminaire. In addition, luminaires with larger surface areas, or luminaires that wash walls or ceiling surfaces with light, may be preferable to luminaires with small, intensely bright apertures.

- The addition of indirect lighting from light-colored walls or ceilings to increase observer adaptation luminance may be considered, thereby reducing the luminance contrast of any direct luminaires viewed against background surfaces, and comfortably adding diffuse light to the illuminance at the eye.

ANSI/IES LP-1-20, Lighting Practice: Designing Quality Lighting for People and Buildings can provide more-general information on designing for improved visual comfort.⁷⁴

5.3.2.5 Temporal Light Modulation. Temporal light modulation (TLM) is cyclic variation in the light output of a lighting system. It can be illustrated as a waveform showing the variation in luminous flux over time. TLM acts as a stimulus, which at frequencies lower than 80 Hz can be *experienced* as flicker, and the word *flicker* is often used generically (but incorrectly) to refer to the variation in light output, or as a general term for the response to TLM over all frequencies.

TLM is not a new phenomenon, but its importance has increased because of the invention of LEDs. LEDs are different from heritage light sources in that they exhibit no inherent persistence. That is, if an LED receives current, it emits light, and when current is switched off, it immediately turns off, without decay in output. The LED is dependent on the driver or driving electronics to deliver current so that its light output is more continuous. Also, unlike with heritage light sources, there are many different driver and electronic designs in use, so that nearly every product has a unique TLM pattern. Many driver circuits use frequent on/off or high/low switching to modulate the light output, especially for dimming. The principal characteristics that affect TLM detection are the light output waveform and the frequency of this variation in light output.

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TLM can cause changes in visual perception. TLM responses include direct flicker, the stroboscopic effect, and the phantom array effect. Direct flicker is most concerning from 3 to 80 Hz, the stroboscopic effect is a concern from 80 to approximately 2,000 Hz, and the phantom array effect can range from below 80 Hz to upwards of 10,000 Hz. Direct flicker can be annoying to sensitive individuals, but a greater concern is photosensitive epilepsy, which can occur in a small subpopulation of people diagnosed with epilepsy.

TLM can sometimes be a trigger for headaches and migraines, and can result in slower visual performance, distraction, and general malaise.⁸⁰ There is little evidence as yet concerning TLM at high frequencies, but there is evidence to show the occurrence of the phantom array effect, which produces lines of dots or parallel lines across the visual field in low light conditions (such as experienced in the nighttime driving of a vehicle). People who are more sensitive to visual discomfort in everyday life appear to be more likely to detect this effect.⁸¹ All of these effects can be avoided through improved electronics design for LED drivers.

TLM metrics and recommended threshold values for different applications are still evolving, but they include Short Term Flicker Indicator (P_{st}^{LM}), the ASSIST Flicker Perception Metric (MP), stroboscopic visibility measure (SVM), percent flicker (modulation depth), the IES Flicker Index, and fundamental flicker frequency. Many of these are problematic, or have to be used in combination with other metrics to understand their meaning. A discussion of metrics and their usefulness will be covered in future IES documents.^{82,196,197,198,204-207}

Manufacturers are beginning to publish these metrics on their product specification pages to help lighting professionals avoid the products with the worst TLM characteristics. The magnitude of TLM may be detected by using a quality handheld TLM meter (also known as a “flicker meter”). Any tests should include dimmed levels, since dimming can introduce increased modulation and lower duty cycles to LED systems that do not exhibit TLM at full output, and many color tunable lighting systems rely on dimming to change from one emitted spectrum to another. It is incumbent on the lighting professional to learn about this issue and apply the

knowledge, especially in applications where health is a main consideration or vulnerable populations may be present.

5.3.2.6 Design Considerations for Occupants. The human response to lighting varies with the individual, and the designer’s role is to consider a diverse range of visual and physiological needs while achieving optimal performance of occupants in the space. Designing to achieve alerting effects cannot be undertaken in isolation from the need to address other needs. This includes balancing the requirements for different occupants and tasks in the space.

Best design practices include those related to communication, daylight and glare management, wayfinding and zoning. These benefit all occupants, and can help make environments more inclusive, thus aligning with the principles of “universal design” as defined by the United Nations Convention on the Rights of Persons with Disabilities (in its Article 2 – Definitions): “the design of products, environments, programmes and services to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design.”

Table 5-1 provides a guidance on some of these strategies. Some may require deviations from, or supplements to, standard design practice. They might appear primarily to address visual responses by creating environments that occupants remain in so that they also receive the intended duration, spectral content, and quantity of light (i.e., illuminance) at the eye to achieve the benefits described in this RP.

5.3.3 Decision Making to Support Physiological Effects. The complexities of designing quality lit environments extend to this RP. To arrive at the “right answer” for a project, the lighting professional will be required to balance the design attributes that can be controlled: the light level at the eye and the spectrum of the light reaching the eye. Some amount of physiological effect inefficiencies arising from decisions related to the spectrum of the light reaching the eye (like finish selections and specified SPD of the luminaire) can be reconciled through considered increases in illumination received at the eye (like availability of daylight, quantities

Table 5-1. Lighting Design Considerations to Provide Inclusive Environments

Recommendation	Design and Lighting Strategy	Population Benefited
Provide Lighting to support communication	<ul style="list-style-type: none"> • Provide wide corridors with vertical illumination to support facial recognition and social interaction. • In public gathering spaces, provide seating facing each other; avoid patterned wall surfaces, sharp lighting contrasts, and backlighting. 	<ul style="list-style-type: none"> • Visually and cognitively impaired individuals, who often face social isolation when unable to easily recognize faces. • Hearing impaired and deaf individuals who rely on reading expressions and/or lips to assist in understanding the spoken word.
Control glare	<ul style="list-style-type: none"> • In daylit spaces, provide overhead daylight apertures (e.g., skylight, clerestory), view fenestration, and electric lighting to balance daylight contribution and/or supplement illumination as needed. • Avoid lighting and materials that create direct glare, reflected glare, shadow, or shine that can be difficult to process. 	<ul style="list-style-type: none"> • Many neurologically diverse individuals are hyper-photosensitive.
Provide wayfinding cues	<ul style="list-style-type: none"> • Provide visual and audible cues to aid navigation. • Provide visual and audible cues about change of status, e.g., open doors, a view panel beside a door, or a visual alert triggered by approach. • Provide visual and audible cues about change of heights or location of exits. 	<ul style="list-style-type: none"> • Visually and hearing impaired individuals.
Define light zones to match activity	<ul style="list-style-type: none"> • Create and define spaces and cues to identify types of activities—e.g., social activity, modes of work—utilizing “sensory stimulus zoning” to designate high stimulus and low stimulus areas. • Provide transitions so that an individual can “recalibrate” to manage the sensory load appropriately. 	<ul style="list-style-type: none"> • Neurologically diverse individuals who are hyper- or hypo-stimulus sensitive.

of luminaires, lumen output of the luminaires, and luminaire distributions). All of these decisions affect the energy consumed by the electric lighting system.

After confirming that the horizontal (E_h) and vertical (E_v) illuminance requirements for vision are met within the space, the melanopic EDI and corresponding melanopic DER may be calculated for each option. Higher melanopic EDI values indicate a higher likelihood that physiological and behavioral effects will be achieved.

5.4 Design Process

When considering the lighting design process, the desire is to incorporate the physiological and behavioral effects considerations without substantially modifying the process of designing for vision. Designing to achieve physiological and behavioral effects of light – in spaces that are under design to receive daylight and incorporate electric light – is a natural extension of the role of the lighting professional who is already designing to meet the visual needs of the occupants. This section provides

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a diagram identifying the design tasks for physiological responses. These tasks are associated with each familiar design and construction phase. Following the diagram are examples of the use of the recommended calculation methodology.

5.4.1 Diagrams of Design and Construction Tasks.

The diagrams in **Figure 5-1** outline the design process for a typical project, and suggests when and how the lighting professional takes light and health issues into consideration during each phase.

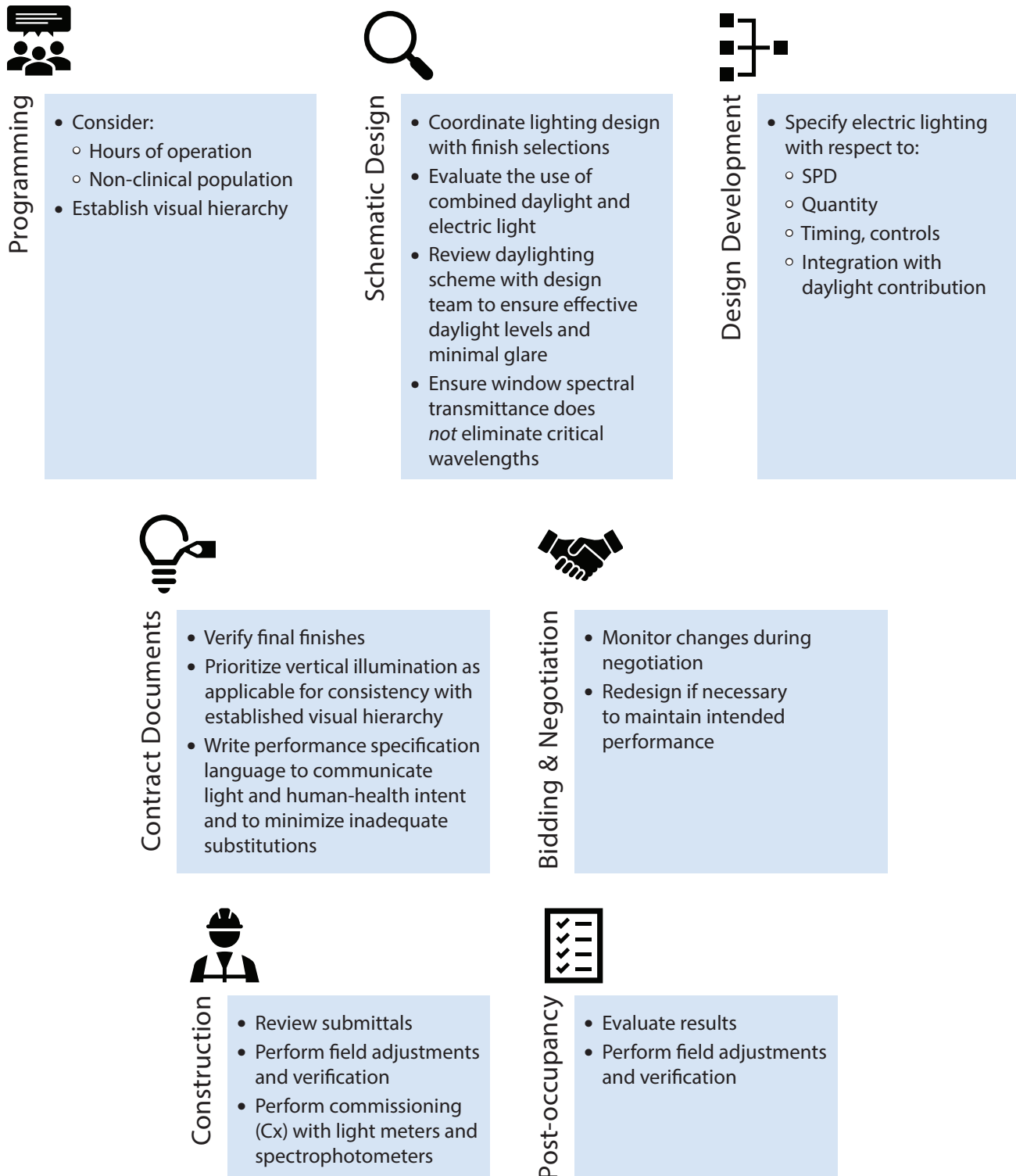


Figure 5-1. Consideration of light and health issues during each design phase. (Image courtesy of Kimberly Mercier)

5.4.2 Predictive Modeling Examples. Computer aided design tools, programs, and applications exist to assist designers with the calculations required to determine the melanopic EDI and the melanopic DER. **Annex A – Metrics and Models** has examples that demonstrate outcomes for an office environment, including attributes and outcome interpretation for each example scenario.

5.4.3 Continuous Improvement Opportunities. Humans interact with the environment in a dynamic fashion. Humans shape the environment, and the environment shapes well-being and performance. Consequently, those who own, manage, and design built environments are responsible for providing conditions that protect and promote health and safety.

Just as happens when designing to meet visual requirements, the designer will be confronted by complexity and unknowns presented by satisfying physiological light requirements.

Evidence-based decision making should be combined with a “do no harm” approach based on actionable insights derived from the available evidence. At the same time, it is imperative to resist the urge to rush the scientific process, but instead engage in continuous reevaluation of conclusions based on emerging evidence.

For those interested in furthering the science, a valuable contribution can be made by collecting and reporting project data for existing lighting conditions of retrofit and remodeling projects, the designed lighting criteria (illuminance values, illuminance and luminance distributions, spectral power distributions, and temporal components, i.e., time of day and duration of lighting exposure), and the as-built conditions. Using the CIE Toolbox⁵⁸ to calculate the lighting inputs to the ipRGC, cone, and rod photoreceptors, and then reporting these values, can potentially lead to scientific advances of optimizing light for human health and well-being.

This reporting paired with pre-occupancy and post-occupancy surveys will provide useful insights for potentially guiding development of lighting application strategies concerning the physiological effects of light.

One required tool would be a light meter that accurately records spectral power distribution at the eye level of the occupant. Of similar importance is calculating melanopic EDI for the lighting environment.^{4,58,60}

5.5 Forecasting Light and Human Health Areas of Interest

The effect of light on human health is an application area of high interest, as evidenced by the ongoing efforts of standards organizations like the CIE and the IES as they work to organize metrics, terminology, research protocols, and prior published findings to present a consensus opinion for utilization by design professionals.

In lighting application areas of interest that rely heavily on discoveries made through research, forecasting activities are influenced by analytic evaluation of market indicators; research funding and construction trends; research trending toward consensus; social interest; and industry demand. The variable, almost fluid, mix of these interests makes forecasting an interesting exercise. This RP presents the research trending toward consensus, the social interest, and the lighting industry technology advancements that fuel demand for new recommendations.

5.5.1 Ongoing Research. Recommendations contained in this RP are made based on research that is ongoing. Ideas and discoveries that are moving toward consensus will demonstrate a significant weight of evidence (identified by the number of published discoveries, the number of laboratories studying the same, and the number of papers in agreement). New ideas and emerging ideas are recognized by a lower weight of evidence (for example, fewer papers from fewer laboratories). It is important to remember that all research begins as an emergent idea with a low weight of evidence; in subsequent iterations of this RP, it is expected that some significant-weight research will have moved toward consensus and some low-weight research will have moved to the significant-weight category.

5.5.2 IES Light and Human Health Committee’s Considerations. While working to build consensus for the publication of this RP, the challenges of creating tangible recommendations—based on a research land-

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scape that is always changing—were laid bare. As related to human health, these questions were considered:

- When is it the right time to tell the design community about a discovery?
- How much research is required to achieve the significant weight expected to provide guideline processes for design or manufacturing?
- Is consensus opinion enough for the incorporation of this information into codes?
- If this is important in normally occupied, interior daytime environments, is it not also important for nighttime environments, or care facilities?

For the IES Light and Human Health Committee, these challenges provide clear guidance for next steps, including continuous maintenance of this RP and future documents on this subject.

5.5.2.1 Continuous Maintenance. This RP is published under the continuous maintenance guidelines of the American National Standards Institute (ANSI) and, as such, provides a true benefit to the lighting practitioner and the light and human health community. Historically, RP document publication was, necessarily, aligned with the cycle of research, discovery, and peer-reviewed publication of findings. While this document is in continuous maintenance, the IES Light and Human Health Committee can provide periodic revisions to the publication as new discoveries and consensus decisions are achieved between publications.

5.5.2.2 Series of Recommended Practices. This RP is the first in a planned series of integrated RPs with the purpose of guiding the light and human health community on the application of light to achieve beneficial physiological responses. The IES Light and Human Health Committee has identified areas of interest for future RPs.

Annex A - Metrics and Models

(This annex is not part of ANSI/IES RP-46-23 Recommended Practice: Supporting the Physiological and Behavioral Effects of Lighting in Interior Daytime Environments, but is included for informational purposes only.)

A.1 Predictive Model Use Example: Melanopic EDI

An open-office environment model is used here as an example for evaluation of five different light sources based on achieving a given average melanopic EDI. Calculations are performed for electric light contributions only, and the window openings are treated as surfaces with 10% average reflection. Five scenarios are presented here.

Luminaire CCT selections are based on common CCT selections for the open office environment. In this example, n is the quantity of calculation points within the room: 40 points in four directions, yielding $n = 160$. The assumptions of 76 cm (30 in.) above the finished floor (AFF) for work plane height and 122 cm (48 in.) AFF for seated eye height are based on industry standards. Melanopic DER and melanopic EDI values were calculated using a D65 reference spectrum^{4,58} at seated eye measurement height. Room surface characteristic outcomes and reference melanopic-EDI mapping diagrams are created with a commercially available software tool.⁸³

A.1.1 Open Office Model Input Values. In this example of an open-office model's use of melanopic EDI, the assumed room characteristics are shown in **Table A-1**.

Table A-1. Room Characteristics for the Example

Room Dimensions	9.80 x 19.58 m (32.16 x 64.25 ft.)
Area	191.38 m ² (2060 ft. ²)
Ceiling Height	3.05 m (10.0 ft.)
Workplane (E _h) Measurement Height	0.76 m (2.5 ft.) AFF
Seated Eye (E _v) Measurement Height	1.22 m (4.0 ft.) AFF

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The room configuration is shown in **Figure A-1**.

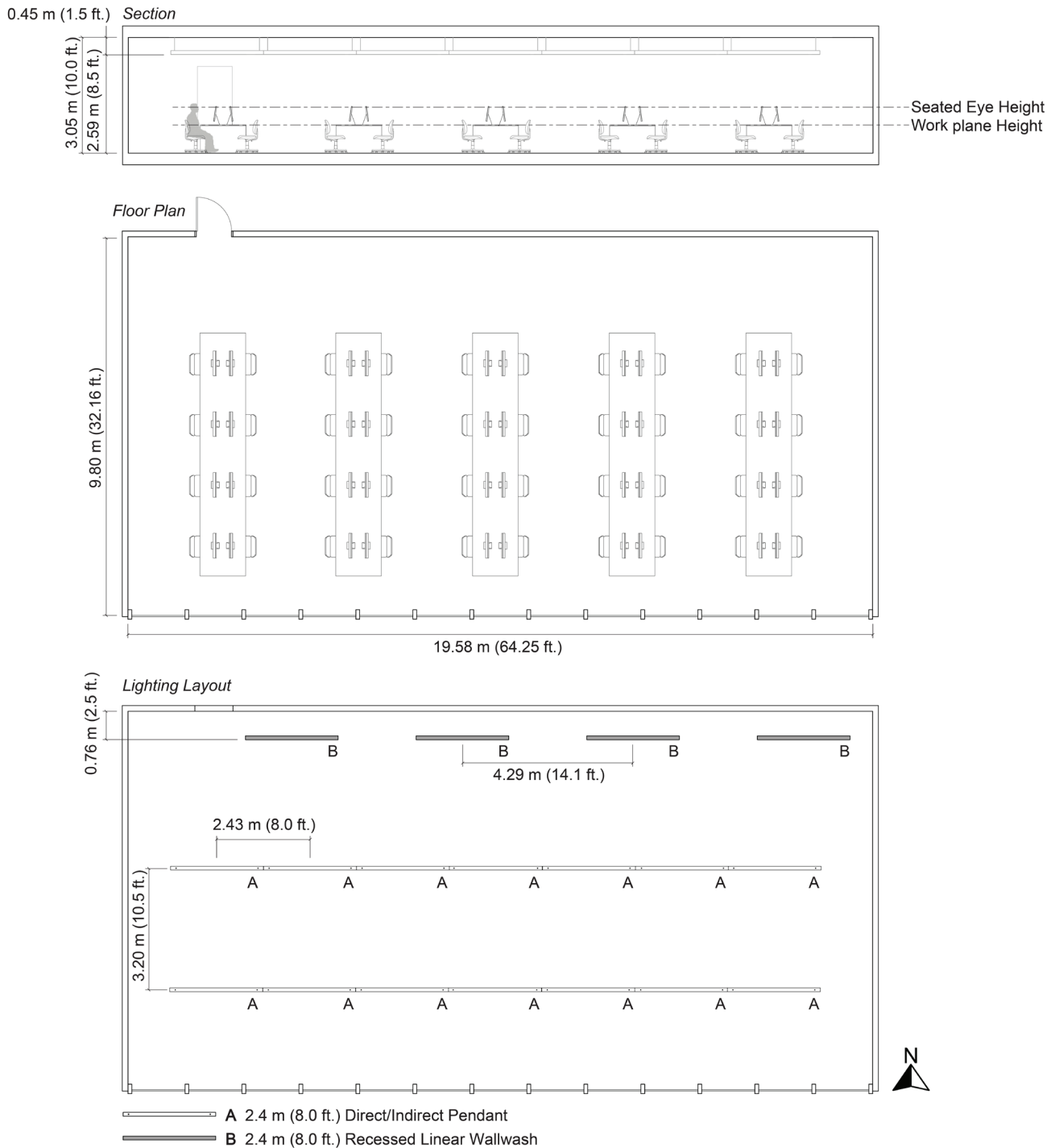


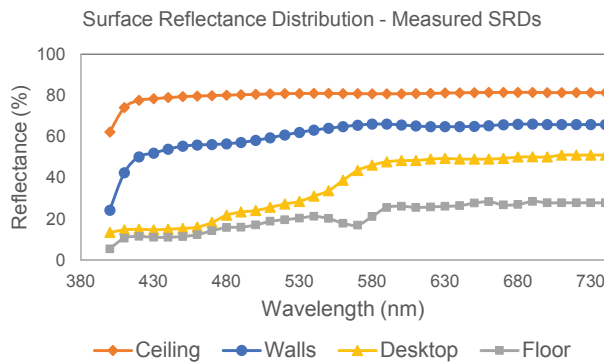
Figure A-1. Open office floor plan and lighting layout. (Courtesy of Jessica Collier, PNNL)

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Room surface characteristics: Figure A-2 shows the spectral reflectance values for the ceiling, walls, desktop, and floor.

Luminaire information: The two types of luminaires used in the model are described in Table A-2. The five SPDs used in the model are shown in Figure A-3. The “SPD A” through “E” nomenclature is arbitrary and is

used in this RP model example to establish a generic naming convention for discussion purposes. In this figure, the luminaire description is as advertised by the product manufacturer, and the distribution diagrams and accompanying tables are outcome values from use of the methodology described in *ANSI/IES TM-30-20, Technical Memorandum: Method for Evaluating Light Source Color Rendition*.⁸⁴



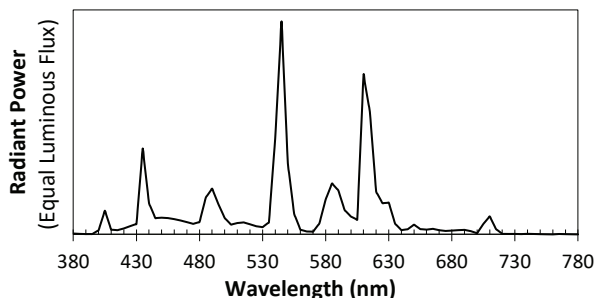
Surface	Description	Avg. (%)	Image
Ceiling	White ceiling	80	
Walls	White paint	60	
Desktop	Blonde wood	36	
Floor	Grey carpet	20	

Figure A-2. Reflectance values of the major surfaces in the model space. (SRD: spectral reflectance distribution)
(Courtesy of Jessica Collier, PNNL)

Table A-2. Luminaire Specifications

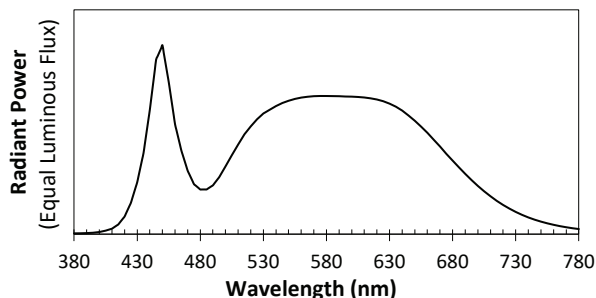
Luminaire	Description	Mounting	Lumens per Watt	Distribution
A	2.44 m (8.0 ft.) Direct/Indirect Pendant	2.59 m (8.5 ft.) to bottom of luminaire	140	
B	2.44 m (8.0 ft.) Linear Wallwash	Recessed in ceiling	150	
Light Loss Factor		0.8		

SPD A



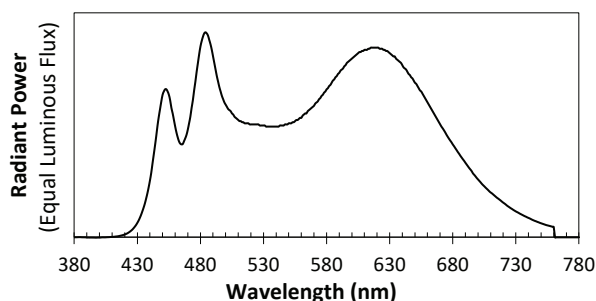
CCT (K)	3971
mDER	0.57
CRI R_a	85
R_f	84
R_g	100
R_{cs-h1}	-9%

SPD B



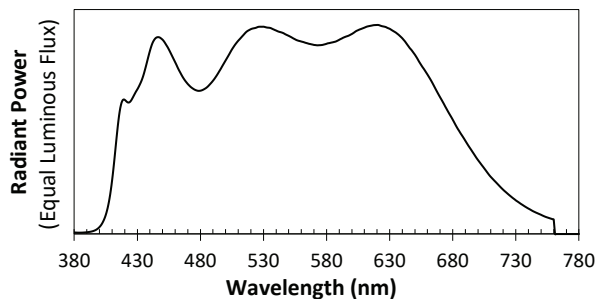
CCT (K)	4268
mDER	0.65
CRI R_a	88
R_f	85
R_g	102
R_{cs-h1}	-6%

SPD C



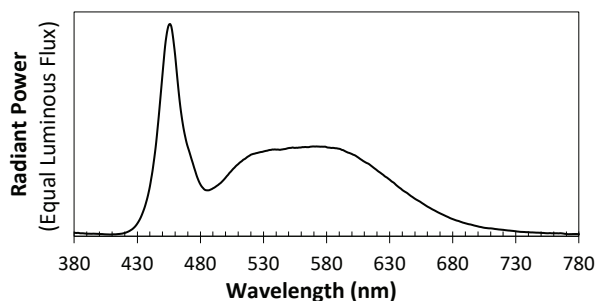
CCT (K)	3782
mDER	0.82
CRI R_a	84
R_f	84
R_g	95
R_{cs-h1}	0%

SPD D



CCT (K)	4933
mDER	0.81
CRI R_a	97
R_f	95
R_g	103
R_{cs-h1}	-1%

SPD E



CCT (K)	6313
mDER	0.90
CRI R_a	85
R_f	82
R_g	93
R_{cs-h1}	-12%

Figure A-3. Spectra and other color characteristics for the five SPDs used in the model. (Note: " R_f " and " R_g " refer to color rendering criteria defined in ANSI/IES TM-30-20.) (Courtesy of Jessica Collier, PNNL)

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A.1.2 Simulation Results. The results of each simulation (for the five SPDs) are shown in **Tables A-2** through **A-6**.

Table A-3. Results for SPD A

	Max.	Avg.	Min.
Horizontal Illuminance (E_h , 0.76 m (2.5 ft.) AFF, lx)	1066	845	453
Vertical Illuminance (E_v , 1.22 m (4.0 ft.) AFF, lx)	775	465	64
Melanopic Equivalent Daylight Illuminance (mEDI, 1.22 m (4.0 ft.) AFF, lx)	419	249	31

n = 160 viewpoints, 4 at each workstation

Table A-4. Results for SPD B

	Max.	Avg.	Min.
Horizontal Illuminance (E_h , 0.76 m (2.5 ft.) AFF, lx)	973	765	403
Vertical Illuminance (E_v , 1.22 m (4.0 ft.) AFF, lx)	700	421	66
Melanopic Equivalent Daylight Illuminance (mEDI, 1.22 m (4.0 ft.) AFF, lx)	430	253	37

n = 160 viewpoints, 4 at each workstation

Table A-5. Results for SPD C

	Max.	Avg.	Min.
Horizontal Illuminance (E_h , 0.76 m (2.5 ft.) AFF, lx)	749	594	333
Vertical Illuminance (E_v , 1.22 m (4.0 ft.) AFF, lx)	566	328	45
Melanopic Equivalent Daylight Illuminance (mEDI, 1.22 m (4.0 ft.) AFF, lx)	437	251	32

n = 160 viewpoints, 4 at each workstation

Table A-6. Results for SPD D

	Max.	Avg.	Min.
Horizontal Illuminance (E_h , 0.76 m (2.5 ft.) AFF, lx)	764	600	341
Vertical Illuminance (E_v , 1.22 m (4.0 ft.) AFF, lx)	555	332	52
Melanopic Equivalent Daylight Illuminance (mEDI, 1.22 m (4.0 ft.) AFF, lx)	425	250	37

n = 160 viewpoints, 4 at each workstation

Table A-7. Results for SPD E

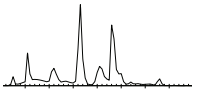

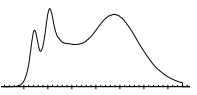
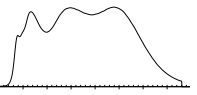
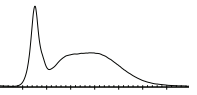
	Max.	Avg.	Min.
Horizontal Illuminance (E_h , 0.76 m (2.5 ft.) AFF, lx)	672	530	453
Vertical Illuminance (E_v , 1.22 m (4.0 ft.) AFF, lx)	494	295	44
Melanopic Equivalent Daylight Illuminance (mEDI, 1.22 m (4.0 ft.) AFF, lx)	420	248	34

n = 160 viewpoints, 4 at each workstation

A.1.3 Simulation Results Summary. The results for the five SPD calculations in the open office model are summarized in **Table A-7**. All else being equal, higher melanopic EDI values indicate an electric lighting solution that is more supportive of physiological effects. In these simulations, the average melanopic EDI was held fixed so that the variations in lumen output, SPD, illuminance and

melanopic DER, required to achieve a given melanopic EDI value, can be more easily understood. The five scenarios illustrate different luminaire SPDs, three of which (A, B, and C) are for the same reported CCT of 4100 K, thereby clearly demonstrating that the CCT of the source is not a singular determinant for the predicted capacity of lighting to stimulate ipRGCs.

Table A-7. Simulation Results Summary

	SPD A	SPD B	SPD C	SPD D	SPD E
					
Melanopic DER:	0.57	0.65	0.82	0.81	0.90
Lighting Power Density (W/ft.²)	1.81	1.65	1.27	1.30	1.16
E_h (lx)					
Max.	1066	973	749	764	672
Avg.	845	765	594	600	530
Min.	453	403	333	341	284
E_v (lx)					
Max.	775	700	566	555	494
Avg.	467	421	328	332	295
Min.	64	66	45	52	44
Melanopic EDI (lx)					
Max.	419	430	437	425	420
Avg.	249	253	251	250	248
Min.	31	37	32	37	34

n = 160 viewpoints, 4 at each workstation

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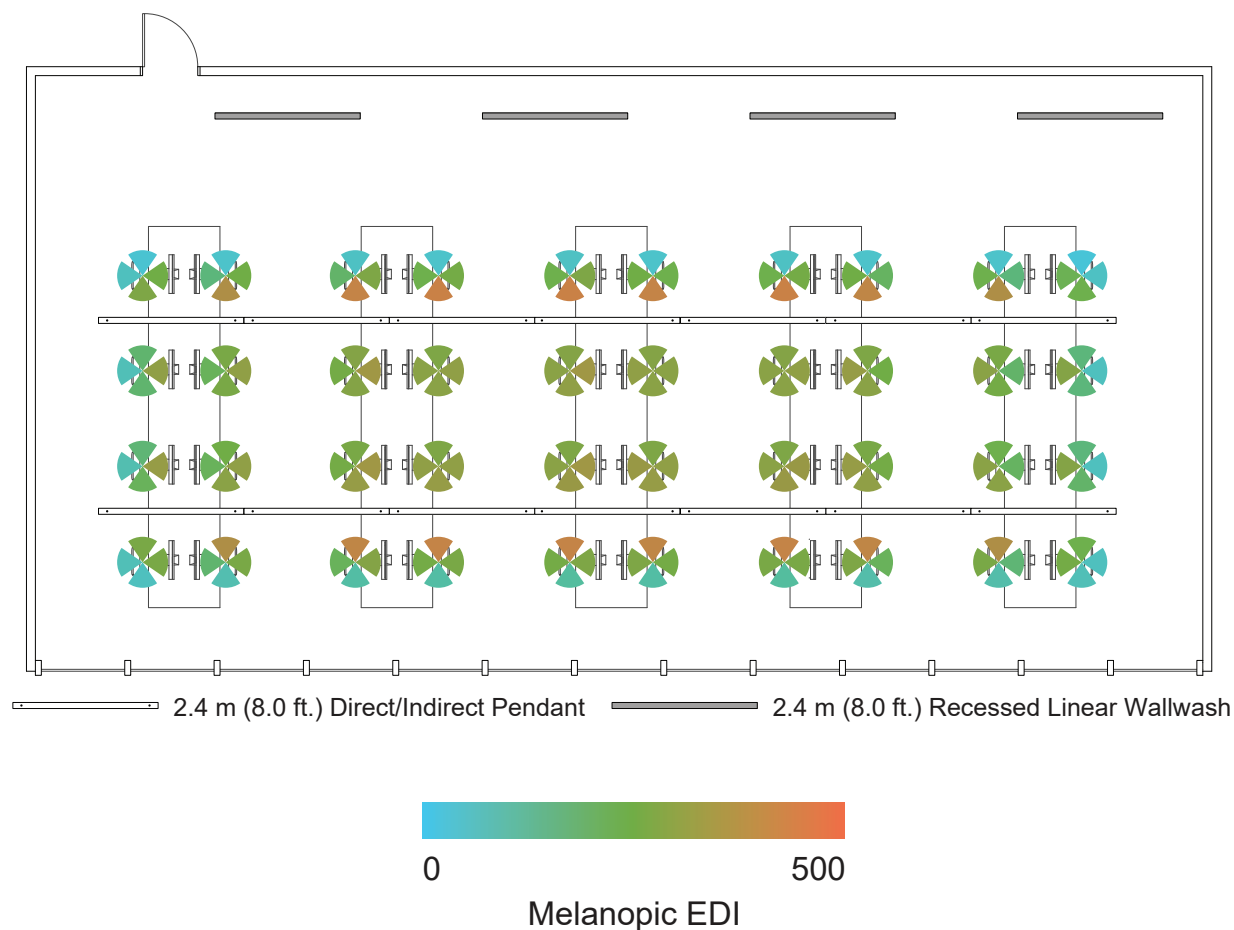


Figure A-4. False-color image of melanopic EDI values (four-direction view plane) Average melanopic EDI = 250 (lx).
(Courtesy of Jessica Collier, PNNL)

As mentioned in **Section 5.2.2.1**, physiological effects can be greatly influenced by daylight from windows and skylights provided that direct and reflected glare are controlled. The spectral balance of daylight varies with time of day, weather, season, and building orientation. For sunrise and sunset at a solar angle of 0° , outdoor daylight averages 298 lux of melanopic EDI. (range between 66 to 504 lux).⁵⁷ At a higher solar angle of 7° , melanopic EDI increased to an average of 2177 lux, and midday levels would be considerably higher.⁵⁷ LED lighting is also capable of providing higher melanopic stimulation than shown in the examples provided in this annex. For example, the newly installed LED lighting system on the International Space Station has three settings, to support “general vision,” “pre-sleep,” and “circadian phase-shifting/alertness.”^{85,86,87} The settings for circadian phase-shifting and alertness can produce a melanopic lux of at least 359 lux.⁸⁷

Spectral choices are important; the introduction of daylight into people’s daily activities and building interiors, the specification of electric light sources exhibiting enhanced performance in the melanopic range of the spectrum, and the selection of finishes that preserve the spectral quality of these choices are of equal importance when creating an environment that is conducive to supporting the intended physiological and behavioral effects of the lighting design. Options for specification-grade interior electric lighting products, with higher melanopic content balanced with desirable values for the remainder of the spectrum, are currently limited. The remainder of the spectrum is important for color rendering and perceived quality of the lighting, and these attributes make the environment enjoyable. For the lighting community, it is important that the environments created are not merely therapeutic, but ones that people enjoy. When people occupy spaces

longer, the lighted space is more likely to have the intended physiological and behavioral effects. As more products are developed to exhibit higher melanopic content within an SPD that demonstrates a more uniform radiant power distribution, the design community will be able to achieve more robust physiological and behavioral responses to light.

A.2 Other Metrics and Models

Although not recommended by this RP, other metrics and models are in circulation and use throughout the industry and a summary description of each is provided for informational purposes; it is anticipated that these metrics and models may change with new findings.

A.2.1 Equivalent Melanopic Lux (EML). In this metric, scaling constraints are applied to the light source spectrum file so that the calculated values from each photoreceptor are similar to the others. To calculate the EML, the space is designed using standard, photopic units. Then the illuminance calculated at the eye is multiplied by the ratio of the calculated melanopic content to the photopic content. EML values from different light sources within the space are additive.

Commercially available and open-access software tools can calculate EML.

A.2.2 M/P Ratio. When considering the M/P ratio, the majority of the alertness response is assumed to be affected by the melanopic response of the ipRGCs to a white light stimulus. The source SPD received from the luminaire manufacturer is run through a calculation spreadsheet and the M/P Ratio is the ratio of lumens weighted by the melanopic response function, to the more familiar $V(\lambda)$ -weighted lumens for photopic-vision. The M/P ratio has been replaced by the melanopic DER term included in the recent CIE standards for measuring lighting for ipRGC functions.

Commercially available and open-access software tools can calculate the M/P ratio.

A.2.3 Circadian Stimulus (CS). CS is based on the combined inputs of all photoreceptors known to contribute to the spectral sensitivity of nocturnal melatonin suppression and is a two-step process. First,

the spectral irradiance of the light incident at the eye is used to calculate circadian light (CL_A), which is the irradiance at the eye weighted to represent the spectral sensitivity of nocturnal melatonin suppression after a one-hour exposure. This weighted value is then converted into CS, which takes into account the absolute sensitivity of the circadian system and represents the effectiveness of that spectrally weighted irradiance at the eye from threshold to saturation.

Open-access software tools can calculate CS.

A.2.4 Recent Translational Approaches. Since the publication of the original analytical action spectra for human melatonin suppression twenty years ago, a number of models and metrics have been proposed to quantify light for circadian, neuroendocrine, and neurobehavioral regulation in humans. For example, one recent model proposes a short-wavelength function with a peak at 477 nm and a range of 438 nm to 493 nm for promoting daytime alertness and productivity.¹⁸⁶ An alternative manufacturer's approach identifies the short-wavelength region with a peak at 490 nm for optimizing daytime ipRGC stimulation. Both of these approaches have been translated into commercially available solid-state polychromatic lighting systems intended to support human vision, health, and well-being during daytime use.

Much is yet to be discovered about the complex anatomy and physiology of the melanopsin photoreceptor system. Further research will open the door to development of more models, metrics and technologies.

Annex B - Scientific Background

This annex is not part of the ANSI/IES RP-46-23 Recommended Practice: Supporting the Physiological and Behavioral Effects of Lighting in Interior Daytime Environments, but is included for informational purposes only.

The study of light effects beyond vision is a relatively new multidisciplinary scientific field (melanopsin was

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discovered only 25 years ago), in which there remains much to learn even though many teams are active. The IES published its first summary document of the state of the science in 2008 (IES TM-18-08), which was reaffirmed in 2018 (IES TM-18-18).¹ Following a recap of fundamentals, this annex provides a brief update of the state of knowledge beyond the information in IES TM-18-18. This is not a systematic review but is intended to provide additional details to expand upon the main text and to demonstrate the general state of the science.

B.1 Light Source and Research Quality Considerations

Researchers whose aim is to provide knowledge that can change lighting practice or the light exposure patterns of a population generally conduct investigations, whether in the laboratory or the field, that relate a light exposure (X) to a physiological or behavioral outcome (Y), under various conditions (Z). The research paper should report in detail on the X , Y , and Z in order to allow readers to evaluate the quality of the evidence produced. Veitch, Fotios, and Houser provided a checklist for readers (and peer reviewers) to use to evaluate research papers and the researchers' reporting of these details.⁸⁹

In the broad domain of light effects on behavioral and physiological responses, one critical element in evaluating research is to understand the light stimulus conditions (the X) that provided the comparisons. Both highly contrived light stimulus conditions and realistic conditions have their place in enhancing understanding. Researchers might add light of a specific wavelength to an otherwise white light source in order to identify parameters that could be controlled through lighting design or light source choices to achieve the desired effects; alternatively, they might use only a specific wavelength or set of wavelengths for the sole purpose of understanding a specific underlying process. More-realistic investigations are more likely to use light sources that emit a mixture of wavelengths (also known as polychromatic light) that appears white. In either case, the X conditions might be representative of real places, or the researchers might deliberately use exposures that are much lower or higher than would typically be found, in order to reveal an underlying process.

The hundreds of studies of all types conducted over the past few decades have demonstrated that the spectrum, quantity, timing, duration, pattern, number of exposures, and history of light exposure all play a role in achieving a physiological response to light.^{1,37} Among the most difficult challenges today is to translate these disparate findings into an expression about the necessary light exposure that accurately integrates the parameters using appropriate quantities that can be measured with traceable instruments.

This task is greatly complicated by the fact that many researchers have provided incomplete information about the light sources they used. For instance, the CCT of a light source provides a general description of the color appearance of that light source but provides no information about its spectral power distribution. Some investigators also reported an illuminance associated with the conditions but did not say where that illuminance was measured. Without knowing the spectral power distribution of the light source, the characteristics of the surroundings that it illuminated, and the light level at the observer's eye, it is impossible to calculate the light exposure associated with any particular investigation—and therefore to compare one investigation quantitatively to another. Recent publications provide guidance to researchers about how to avoid this problem,^{6,90} but readers can also use this guidance to evaluate the quality of studies as they read.

B.2 Learning That Response to Light Was Not Dependent on Vision

It had been thought that all responses to light by the eye were driven by light detected by rod and cone photoreceptors, which had been identified through studies of vision. In the 1990s, however, studies in color blind or blind humans^{68,69,70,91,92} and animals^{93,94,95} showed that damage to rod- and cone-based photoreception did not prevent circadian resetting or melatonin suppression responses to light. This led researchers to predict the presence of a non-rod, non-cone photoreceptor system in the mammalian eye.

A candidate photopigment, melanopsin, was discovered in 1998 and was found to be present in a small subset of retinal ganglion cells in the mammalian eye.^{96,97} The melanopsin-containing ganglion cells were

found to be intrinsically light-sensitive, with a peak sensitivity in the short-wavelength (“blue”) light range, around 480 nm.^{10,26,98,99} These were labeled intrinsically photosensitive retinal ganglion cells, or ipRGCs.

It was thought that these cells formed a completely separate system from vision, for these cells connect to brain centers other than the visual cortex. The most studied pathway, through the retinohypothalamic tract, connects to the suprachiasmatic nucleus of the hypothalamus. This connection to the circadian (24-hour) body clock allows light and dark signals to reset daily rhythms of sleep, hormones, temperature, alertness, performance, and other 24-hour rhythms, suppressing nocturnal melatonin production, elevating cortisol in the morning, and increasing heart rate and temperature at night.^{29,37,42,100,101,102}

On further study, however, it has become clear that the various retinal cells are highly interconnected. Removal of melanopsin alone caused degradation of physiological responses to light by 40% to 60%^{103,104} but did not abolish the responses, suggesting a potential role for rods and cones in contributing to physiological response. Removal of rods, cones, and melanopsin, however, abolished all responses to light.¹⁰⁵ While melanopsin has been confirmed as the primary photopigment mediating these physiological responses to light, rods¹⁰⁶ and cones^{107,108} also contribute under certain circumstances. All of these physiological responses to light cited in these rodent studies, including rod, cone, and melanopsin inputs, are mediated through the ipRGCs.

B.3 Photodetection and Visual System Connections

Since 2008, at least five morphological types of rodent ipRGCs have been identified. These subtypes receive diverse rod and cone input from the inner retina, project this information to different nuclei in the brain, and are physiologically diverse.^{23,25,109,110} This means that information about light might influence a broad range of behaviors and processes that have, as yet, not received extensive research attention, particularly in humans. For example, M1 cells stratify in the OFF layer of the inner retina and project to the olivary pretectal nuclei (OPN) and the suprachiasmatic nuclei, where they are thought to participate in the pupillary light reflex and circadian

photoentrainment. In contrast, the M2, M4 and M5 cells stratify in the ON layer of the inner retina and project to the dorsal lateral geniculate nuclei, periaqueductal gray, and amygdala, which suggests contributions to the circuitry for image formation as well as to pain, fear, and anxiety.²⁴ Furthermore, with the exception of M1 cells, the other four types of mouse ipRGCs have receptive fields with antagonistic ON-center, OFF-surround regions, which suggests that these cells perform spatial analysis.^{23,111} Indeed, the five types of mouse ipRGCs detect different speeds of motion, raising the possibility that the ipRGCs contribute to motion detection.²³

In primates, a capacity for color discrimination by ipRGCs that receive color-opponent (blue OFF, yellow ON) input from cones has been observed.¹⁰⁷ There is also psychophysical evidence that melanopsin directly contributes to color vision in humans.^{112,208} Recently, isolation studies of melanopsin, through methods of silent substitution, have shown that melanopsin photoreception contributes to human visual detection, temporal and color processing, direct cortical stimulation, and evoked conscious perception.^{113,114,208,209}

There exists species variability and diversity of ipRGCs, as shown in studies from several laboratories.^{23,24,25} Taken together, the emergent work on ipRGC diversity in rodents, tree shrews, non-human primates, and humans indicates that there are some common organizational aspects of ipRGCs, while other features are clearly species specific. This presents a challenge to lighting design for humans. It is evident that the melanopsin-containing ipRGCs play a variety of roles in vision, including image-forming responses. Consequently, it is inappropriate to classify the physiology regulated by the ipRGC photoreceptive system as “nonvisual” or “non-image forming.” Importantly, not all of the biological and behavioral effects of light in various species may be regulated by the same blend of ipRGC, rod, and cone inputs. How diverse rod and cone inputs contribute to ipRGC photoresponses remains an area of intense study.

B.4 Circadian, Neuroendocrine, and Neurobehavioral Responses To Light

B.4.1 Melatonin Suppression. Melatonin is instrumental for the regulation of sleep/wake cycles and

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circadian functioning. It is released at night, under dark conditions; exposure to light when melatonin is being released causes a rapid suppression of the melatonin release. This phenomenon was the basis for most of the investigations^{21,22} that led to the development of the melanopic action spectrum codified in CIE S 026/E:2018.⁴ Subsequent studies are broadly consistent with these initial findings, demonstrating a comparable dose response to monochromatic or narrowband short-wavelength light^{14,113,115-121} or significant melatonin suppression by single-intensity “blue light” exposures.^{122,123}

Melatonin suppression studies have added to the evidence that the various photoreceptor systems are interconnected. For example, Gooley and colleagues¹²⁴ compared the melatonin suppression response during exposure to 6.5 hours of either 460-nm or 555-nm monochromatic light at night. The 555-nm light was assumed to be transduced through the photopic system (medium- and long-wavelength cones), and the 460-nm light was assumed to be transduced via melanopsin. In the early stage of the exposure, both conditions delivered a similar melatonin-suppression response, but over time the response to the 555-nm light decayed (i.e., melatonin release resumed), whereas the 460-nm melatonin-suppression response continued. Thus, while the photopic system appears to be able to contribute nearly equally to melanopsin-mediated responses at the start of a light exposure, or at low illuminances, melanopsin dominates the responses at higher light levels and over longer durations.

Other investigations also suggest that the short-wavelength cones (S-cones) influence the melatonin suppression response. Revell and Skene¹²⁵ compared three intensities of white and monochromatic 479-nm light, equated for melanopsin-activating photons, and showed that (in addition to the expected dose-dependent effects of intensity) there was greater melatonin suppression in response to the polychromatic white light than in response to the monochromatic light. A more detailed comparison of various monochromatic lights (alone and in combination) and two polychromatic lights also showed that (at the photon densities studied) melanopsin stimulation alone could not account for all responses, implying a role for the short-wavelength cones.¹²⁵

Figueiro and colleagues have also reported that the melatonin suppression response is not explained by ipRGC stimulation alone,¹²⁶ and have proposed a number of mechanisms that may mediate the response, including rods¹²⁷ and S-cones.¹²⁸ Ongoing research explores the potential for encoding spectral information in ipRGC responses and the possibility of spectral opponency being a reason for different responses to polychromatic light exposure as compared to monochromatic exposure, but the evidence is not viewed as conclusive at this time.¹²⁹

There has been considerable interest in reducing the short-wavelength content of light exposures in order to reduce melatonin suppression at night, either by directly changing the spectrum of a light source (including display screens) or by changing the spectrum of the light received at the eye by using glasses that filter short-wavelength radiation. Each approach has been shown to have the expected effects on melatonin suppression.¹³⁰⁻¹³⁷ Individual differences exist in the degree of response to this effect, which appear to depend on genetic differences in the clock genes¹³⁸ and on the sex of the observer.¹³⁹

B.4.2 Circadian Phase Setting. Melatonin suppression and circadian phase setting are now known to be distinct processes.⁶⁴ Melatonin suppression is comparatively easy to study, whereas circadian resetting is more difficult. Assessing changes in circadian phase (as compared to melatonin suppression) requires greater control of other environmental factors. Laboratory circadian studies often require several days' residency for participants, and controlled schedules of light and dark exposures, meals, and sleep times. Field investigations demand thorough characterization of light exposures and complex measurements of circadian phase throughout the investigation. Nonetheless, with the increasing ease of travel, the improved recognition of the importance of sleep, the widespread use of shift work, and the interest in performance relative to circadian cycles, understanding circadian resetting is scientifically and socially important.

As described in **Section 3.2 Circadian Regulation**, the timing of exposure to light determines whether that exposure phase-shifts the clock to an earlier time (phase

advance) or to a later time (phase delay). Under normal conditions, light exposure in the late evening will delay the circadian system to a later phase, and light in the early morning will advance the circadian system to an earlier phase.^{63,64,140,141,142}

There is a non-linear relationship between light duration and both circadian resetting and melatonin suppression responses at night, such that shorter light exposures are more effective on a per-minute basis.^{30,31} Similarly, intermittent (as opposed to continuous) exposure induces a greater phase shift than predicted by a simple linear response to light duration,^{32,33} and, at very short frequencies (1 ms per minute over an hour), has been suggested to be more effective than continuous exposure at resetting the circadian clock.^{200,201}

The spectral sensitivity for circadian resetting effects of light has been investigated in studies comparing different wavelengths, although full action spectra are not yet available. Short-wavelength sensitivity has been demonstrated for resetting the timing of the circadian clock (typically measured from the timing of melatonin onset or temperature rhythms under controlled conditions), for phase-advance shifts after early morning light exposure,^{123,217,218} for phase-advance shifts early after morning light exposure, for phase-delay shifts following light exposure during the night,^{121,124} and for both advances and delays according to a standard phase response curve (PRC).^{63,142}

There is also evidence that the sensitivity of the circadian system to light may be determined by prior light exposure over the previous hours and possibly days,^{34,35,36} with increased prior exposure to light “desensitizing” the system and causing a modest reduction in the magnitude of the subsequent response to light. While these principles are established, their utility for improving lighting for general interior daytime functioning is not yet known.

B.4.3 Alertness.

B.4.3.1 Measuring Alertness. Research relative to direct alerting responses is of keen interest; there is an innate understanding of the value of being alert—for example, at work, at school, while driving, and when

interacting with others. Alertness is a complex concept, defined differently (sometimes vaguely) by different authors.^{143,144} For the purpose of this document, the definition from the American Psychological Association was adopted: “the state of being awake, aware, attentive, and prepared to act or react.”³

Scientists assess alertness in three ways: by measuring physiological responses; by using behavioral measures to assess cognitive performance; and with self-reported (subjective) measures. Physiological measures of alertness include waking electroencephalogram (EEG) activity, heart rate, heart rate variability, blood pressure, and pupil dilation.^{40,42,144} Behavioral measures include sustained attention (vigilance), working memory tasks, and executive control tasks.^{152,153}

There are several commonly used self-report measures of alertness and of its converse, sleepiness, including the Karolinska Sleepiness Scale (KSS) (a single question with a 9-point response scale) and various multi-item checklists and scales.^{40,41} There is variation in the validity and reliability of these measures,¹⁴⁶ and researchers are required to choose the measure that best fits the context in which it will be used.¹⁴⁷

Measures of sleepiness are used to measure the converse of alertness, but these are complicated by the fact that sleep is governed by multiple processes.^{147,149,150} Alertness and performance levels, even in the absence of light¹⁴⁸ are determined by two oscillatory processes: homeostatic regulation (whereby alertness depends on prior time awake) and circadian regulation (which governs alertness according to an endogenous circadian rhythm).^{149,150} A third process¹⁵⁰ describes the influence of sleep inertia, whereby the “grogginess” experienced upon waking takes several hours to dissipate.¹⁵¹ A fourth process, the time course of the build-up and recovery of sleepiness following acute or chronic sleep loss, also appears to affect current alertness levels.^{152,153}

The methods used to assess alertness all have limitations. Self-report, physiological, and performance measures of alertness do not always follow the same pattern of results.^{40,41,43,152,153} This can occur for many reasons, including uncontrolled variables, the sensitivity of the

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measures, and possibly because multiple processes are involved. In attempting to draw general conclusions, researchers look for consistent patterns across the various categories of measures within what are thought to be distinct processes.

B.4.3.2 Nighttime. Although this document focuses on daytime light exposures, the starting point for knowledge of the effects of light on alertness was studies of nighttime exposures to white light of varied illuminance levels. *Nighttime* in this context means biological night, defined as the time between melatonin onset and the end of melatonin synthesis. The length of biological night is typically about seven hours.¹⁵⁴ These investigations have revealed a non-linear dose-dependent effect, with a sigmoidal shape in which there is little response to exposures below approximately 10 lx, then a rapid increase in response, and saturation of response occurring between 500 and 1,000 lx at the eye.^{29,100} Recalculating the exposures using an early version of the calculated melanopic illuminance⁶ led to a stronger prediction of the effect on KSS scores (higher explained variance and smaller confidence intervals).^{215,57}

Research on the effect of light exposure at night suggests a different spectral sensitivity for alertness than for melatonin suppression. For example, a comparison of two light levels of narrowband light—blue (470 nm at 10 and 40 lux) and red (630 nm at 10 and 40 lux)—on brain activity measured with an EEG showed that blue light and red light each decreased alpha power (8 to 12 Hz) and increased beta power (12 to 30 Hz) compared to a dim light condition (less than 5 lux at the eye at nominal 2700 K). Sleepiness and performance did not differ across conditions or when compared to darkness.¹⁵⁵ In another study,¹⁵⁶ Figueiro and colleagues showed that, compared to remaining in dim light, participants had significantly faster reaction times in the GO/NO-GO test after exposure both to red light (631 nm, 213 lux at the eye, 110 microwatts per square centimeter [$\mu\text{W}/\text{cm}^2$]) and to white light (361 lux at the eye, 110 $\mu\text{W}/\text{cm}^2$). Compared to dim light exposure, power in the alpha and alpha-theta regions was significantly decreased after exposure to red light. Several laboratories, however, have reported short-wavelength sensitivity when comparing exposure to monochromatic 460-nm light

versus 555-nm light for improvements in subjective alertness and performance.^{130,133,134,195,219}

B.4.3.3 Daytime. There is no comparable dose-response curve for the effects of interior daytime light levels on alertness to correspond to the nighttime curve described in the previous section. As noted in **Section 3.3.1 Immediate Responses** and **Section 3.3.2 Cumulative Responses**, the evidence for light level effects on daytime alertness is inconclusive, except for self-reported alertness.^{40,41} Among the reasons for the inconclusive results are small sample sizes and experimental conditions in which the lowest exposures might be higher than the saturation value for certain responses.⁴¹

Similarly, studies that varied specific wavelengths in order to study fundamental processes have also obtained mixed results for different outcomes and experimental protocols. Light stimuli designed to target the ipRGCs, as compared to the photopic system (460 nm vs. 555 nm), showed faster auditory reaction time and EEG responses typical of a more alert state.¹⁵⁷ That study, however, observed no effect on self-reported sleepiness during daytime. These findings were consistent with a later report for afternoon exposure,¹⁵⁸ although long-duration morning exposures were not reported to be alerting, as also reported in an earlier study.¹⁵⁹ A 30-minute exposure to blue (485 nm) versus orange (622 nm) narrowband light after lunch did not improve psychomotor vigilance task (PVT) performance but did enhance autonomic arousal.¹⁶⁰ One experiment used a light visor to supplement room lighting with either high illuminance (2,000 lx) provided by broadband light peaking at 460 nm, or low illuminance provided by narrowband radiation peaking at 660 nm, for 15 minutes prior to a demanding cognitive task.¹⁶¹ They observed no effects on subjective sleepiness or cognitive performance.

As noted above, there is limited evidence from field investigations to suggest that by increasing the light exposure directed at ipRGC wavelength sensitivity, one can increase self-reported alertness.^{49,79} The first of these field experiments⁷⁹ compared a fluorescent lamp deliberately chosen to have little short-wavelength radiation (and a CCT of 2950 K) with one that had a

great deal of short-wavelength radiation (and a CCT of 17,000 K). A different light source was installed on each of two floors of the office building, and the two resulting groups were compared. The participants on the floor with the higher-short-wavelength lamp reported lower fatigue, higher alertness, lower daytime sleepiness, and higher work performance. In addition to the difference in spectral power distribution between the two floors, the higher-short-wavelength area also had an approximately 33% higher vertical illuminance (170 lx versus 128 lx), making it unclear whether the difference was attributable to the spectrum of the light or the light level.

The experimental control was tighter in the subsequent crossover study at a different workplace,⁴⁹ in which each participant was exposed to both lighting conditions for one month in a counter-balanced order between two floors ($n = 104$). Subjective ratings of alertness, mood, sleep quality, performance, mental effort, headache, and eye strain were collected throughout. The 94 participants included in the analysis showed statistically significant improvements in self-reported measures of alertness, positive mood, performance, evening fatigue, irritability, concentration, and eye discomfort during the month of exposure to 17,000 K, as compared to 4000 K. They also reported reduced daytime sleepiness and improved sleep quality at night.

Not all such studies have observed similar effects. A daytime study of participants who were extremely, chronically sleep-deprived did not show any improvement in alertness or performance during exposure to 200 and 400 lux of 17,000-K fluorescent light compared to 200 lux of 4000-K light.¹⁵²

Replication is a cornerstone of the scientific method, as it provides confidence that a result reflects a real phenomenon rather than a chance occurrence. One particular classroom lighting study, conducted in three countries (the Netherlands,¹⁶² Germany,¹⁶³ and the United States¹⁶⁴) and published in two different years, has been replicated in several studies and with classes of varying grades. The study compared a standard, fixed classroom lighting scheme to a dynamic lighting system with various preset combinations of light source spectrum and illuminance. The hypothesis was that

the use of dynamic lighting would positively influence the concentration and reading speed of the students. Covariates differed between the studies but, generally, embraced parameters such as baseline performance scores, age, gender, expectation of the intervention, reading proficiency, and health. Disturbance variables such as noise, temperature, humidity, carbon dioxide levels, and daylight contributions were not controlled.

The instructors were provided with four preset scenes: "Normal," 3000 to 4000 K and 300 to 500 lx on the desk surface (this was the fixed condition in the comparison classrooms); "Energy" (650 lux, 12,000 K measured at the eye), recommended for use typically for 15 minutes in the morning and after lunch; "Focus" (1,000 lux, 6500 K) for use typically for 45 minutes in the morning and during challenging tasks such as testing; and "Calm" (300 lux, 2900 K), for use typically for 45 minutes and following the Focus period, to provide relaxation for quiet time activities. Special data collection tests of attention, performed under the Focus setting in the experimental classrooms, showed in some cases that performance on these tests was better in the classroom with the dynamic lighting. What is unclear from the results is whether these effects were associated with any specific photoreceptor stimulation by the higher light levels, the light source spectrum, or both; or whether there was an association of the special setting with the test taking that led to the observed performance.

There have been other field investigations in which a small number of classrooms have been equipped with light sources varying in spectral power distribution or the light levels they provided, or both. Some have reported that light sources designed to increase ipRGC stimulation improved concentration.¹⁶⁵ Classroom investigations are very difficult because the correct research design is a nested design in which students are in classrooms, and the classroom (not the individual student) is the proper unit of analysis. There have been no properly sized school investigations in which this research design has been used, but this would be the only way to control for the differential effects in teaching, pre-existing abilities, participant expectancies, and other potentially confounding variables.¹⁶⁶

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B.4.3.4 Evening. Evening light exposures that stimulate ipRGC effects have been shown to affect both performance and subjective sleepiness. For example, Chellappa and colleagues demonstrated¹⁶⁷ enhanced psychomotor performance and subjective alertness during a 2-hour, 30-lux exposure to 6500-K white light, compared to 2500-K light. The alerting effects continued for a period of time after lights were extinguished, such that it took longer to fall asleep, the amount of slow-wave (deep) sleep was reduced, the REM sleep was altered, and there was an increased feeling of tiredness upon waking.

B.5 Effects of Age

In healthy humans, the ocular cornea, aqueous humor, and vitreous humor are clear tissues that transmit nearly 100% of visible and ultraviolet wavelengths (down to 300 nm) to the retina, with little age-related change in the transmission characteristics. In sharp contrast, the crystalline lens in the human eye develops a yellow pigmentation with age, which acts as a filter that significantly reduces the total transmission of radiant energy to the retina, particularly in the shorter-wavelength portion of the spectrum.^{168,169} In general, transmission of longer-wavelength visible light is not substantially different between age groups. The lenses of newborn children and of young adults transmit some ultraviolet radiation to the retina. In contrast, the lenses of adults aged 60 to 69 do not transmit ultraviolet radiation to the retina, and there is a significant reduction of wavelengths transmitted in the violet, indigo, blue, and green portions of the visible spectrum.¹⁷⁹ Thus, with aging, the ocular lens modifies the total quantity of light as well as the balance of wavelengths that reach the retinal photoreceptors. Such age-related changes have the potential for a significant influence on systemic physiology.

It is accepted that age-related changes in lens transmission can have significant impact on human

vision.^{123,170,211,212} Given the high sensitivity of the ipRGCs to short-wavelength visible light, the age-related changes in lens transmission appear also to affect the physiological effects of light on melatonin regulation and sleep physiology. A controlled laboratory study compared melatonin suppression in young versus older women (mean ages 24 versus 57 years) with exposure to short-wavelength monochromatic light at 456 nm.¹²⁷ The results showed a significant reduction of melatonin suppression in the older women, which the investigators interpreted to be a consequence of changes in lens transmission.

Similarly, an epidemiological study of 970 randomly selected individuals aged 30 to 60 years illustrated a significant increase in sleep disturbances associated with decreased transmission of short-wavelength light in the lenses of older adults.¹⁷¹ The investigators concluded that filtration of blue light by the aging lens resulted in disturbance of circadian entrainment, thereby increasing the risk of sleep disturbances.

Such findings suggest that lighting levels need to be specified relative to the age of the occupants in the designed environment so as to optimize vision as well as circadian, neuroendocrine, and neurobehavioral regulation. Hence, the spectral quality and quantity of light that is best for an elementary school might be different from the lighting needed for a retirement community. Where environments contain people of widely different ages, it may be challenging to provide recommended light levels that are ideal across the age distribution, both for visual tasks and when considering lighting to maintain alertness. CIE S026:2018 includes guidance on scaling the alpha-opic quantities to reflect age-related changes in lens transmission. Additional guidance for lighting spaces occupied by older adults is available in *ANSI/IES RP-28-20, Recommended Practice: Lighting and the Visual Environment for Older Adults and the Visually Impaired*.¹⁷²

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Process for Change to an ANSI/IES Standard under Continuous Maintenance

This standard is maintained under continuous maintenance procedures, for which IES has an established and documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the standard. Committee consideration will be given to proposed changes by June 30 of any given year for proposed changes received by the IES Director of Standards no later than December 31 of the previous year.

Submittal Format

Proposed changes must be submitted to the IES Director of Standards in the announced published format. However, changes may be accepted in an earlier published format, if the differences are immaterial to the proposed change submittal. If the Director of Standards concludes that a current form must be utilized, the proposer may be given up to 20 additional days to resubmit the proposed changes in the current format.

Specific changes in the text or values are required and must be substantiated. Any change proposals that do not meet these requirements will be returned to the proposer. Supplemental background documents to support changes submitted may be included.

Submission to the Committee Chair

The Director of Standards shall forward proposed changes received on appropriate forms to the committee chair for assigning to committee members (responders) to develop responses to submitters of proposed changes.

Review and Clarification

Responders shall review proposals and should contact the proposer if necessary for clarification.

Response Recommendation

Designated responders shall draft a recommended committee response, including any recommended changes to the standard. The 'responders' recommended responses shall be submitted to the committee chair in electronic form usable by Society Staff, including any recommended change to the standard in response to proposals received.

Options for Committee response are limited to:

- a) Proposed change accepted for public review without modification
- b) Proposed change accepted for public review with modification
- c) Proposed change accepted for further study
- d) Proposed change rejected

The responders shall provide reasons for any recommendation other than option (a) above.

The designated responders shall not recommend option (c) unless the further study can be completed by October 1 of that year, and providing the Committee can then vote for option (a), (b), or (d) no later than November 15 of that year.

Editing

The Committee chair or his or her designee shall edit the draft responses and circulate the edited drafts to the committee for review.

Form for Proposing Change to an ANSI/IES Standard under Continuous Maintenance

NOTE: Use a separate form for each comment. Submit to the Director of Standards, IES, 120 Wall Street, 17th Floor, New York, NY 10005-4001. Email: standards@ies.org. Fax: 212-248-5017.

1. Submitter: _____
Affiliation: _____
Address: _____
City: _____ State: _____ Zip: _____ Country: _____
Telephone: _____
Fax: _____
E-mail: _____

I hereby grant the Illuminating Engineering Society (IES) the non-exclusive royalty rights, including non-exclusive rights in copyright, in my proposals. I understand that I acquire no rights in publication of the standard in which my proposals in this, or other analogous, form are used. I hereby attest that I have the authority and am empowered to grant this copyright release.

Submitter's signature: _____ Date: _____

2. Title of publications and year published _____

3. Clause (section), sub-clause or paragraph number; and page number: _____

4. My proposal (check one):

- ☐ Change to read as follows
- ☐ Delete and substitute as follows
- ☐ Add new text as follows
- ☐ Delete without substitution

Use underscore to show material to be added (added) and strikethrough for material to be deleted (~~deleted~~). Use additional pages if needed.

5. Proposed change:

6. Reason and substantiation:

Select as applicable:

- ☐ Additional pages are attached. Number of additional pages: _____
- ☐ Attachments or referenced materials cited in this proposal accompany this proposed change.

Please verify that all attachments and references are relevant, current, and clearly labeled to avoid processing and review delays. Please list your attachments here:



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