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International Standard

CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light

Système CIE de métrologie des rayonnements optiques dédié à la réponse à la lumière des cellules ganglionnaires photosensibles de la rétine (ipRGC)

CIE-System für die Metrologie optischer Strahlung für ipRGC-beeinflusste Antworten auf Licht

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Foreword

International Standards produced by the Commission Internationale de l'Eclairage are concise documents on aspects of light and lighting that require a unique definition. They are a primary source of internationally accepted and agreed data which can be taken, essentially unaltered, into universal standard systems.

This CIE Draft International Standard has been prepared by Joint Technical Committee (JTC) 9 "CIE system for metrology of ipRGC influenced light response" of Division 1 "Vision and Colour", Division 2 "Physical Measurement of Light and Radiation", Division 3 "Interior Environment and Lighting Design", and Division 6 "Photobiology and Photochemistry" of the Commission Internationale de l'Eclairage, under lead of Division 6.

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CIE System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light

Introduction

There is strong scientific evidence that light is not only essential for vision but also achieves important biological effects relevant for human health, performance and well-being that are not dependent on visual images. Many of these “non-image-forming” (NIF) effects of light (also sometimes denoted as “non-visual”) originate in the eye and therefore are distinct from skin-mediated responses to optical radiation (e.g. vitamin D production, skin cancer or solar dermatitis). This document focuses on the eye-mediated non-image-forming effects of light. These effects depend on the spectral power distribution, the spatial distribution, the timing and the duration of the light exposure. They also depend on person-specific parameters such as an individual’s circadian phase and history of light exposure. In the vision sciences and in photobiology it is often helpful to define standard physical quantities based on action spectra (that describe an average sensitivity to light). The connection between these quantities and actual physiological responses to light can then be studied using common light measurement concepts, which are not themselves dependent on observing any individual’s subjective responses.

Light is the main synchronizer of the human biological clock. It can shift the phase of the circadian rhythm and determines the timing of the sleep/wake cycle. Light can cause acute suppression of the nocturnal release of melatonin. There are also reports that light can increase heart rate, improve alertness, alleviate seasonal and non-seasonal depression, influence thermoregulation, and it can affect the electroencephalogram (EEG) spectrum. Exposure to light elicits fast responses (i.e. in the range of milliseconds and seconds) in the pupillary reflex or in brain activity.

Lighting standards, regulations and practice often focus on visual and energy efficiency aspects of light and do not address non-image-forming responses to light. This can result in lighting conditions that compromise human well-being, health and functioning.

The above-mentioned biological effects of light are elicited by stimulation of ocular photoreceptors. The classical receptors for vision, the rods and cones, are relatively well understood and characterized by existing CIE publications. Pioneering work over the past 25 years revealed that the eye has another kind of photoreceptor. This photoreceptor plays an important role in non-visual effects of light and has a peak sensitivity in the shorter wavelength part of the visible spectrum. Such photoreceptors are known as intrinsically-photosensitive retinal ganglion cells (ipRGCs), and their intrinsic photosensitivity is based on the photopigment melanopsin that is contained within them.

For non-image-forming effects of light, a description of optical radiation solely according to the photopic action spectrum is not sufficient. Moreover, there is no single action spectrum for non-visual responses. The actual NIF effects due to ocular exposure to light depend on the combined responses of all photoreceptors and there is good evidence for the potential for all receptor types to contribute to these responses.

The scientific literature contains examples of variation in the parts played by each photoreceptor type for eliciting several non-visual effects according to (retinal) irradiance and other light exposure properties like context (subjective time, prior light history, light adaptation, sleep pressure), duration, spectrum and variability over time. Other features such as spatial distribution of light, field of view and time of day may also be shown to influence non-visual effects. If uncertainty regarding the relative photoreceptor inputs to any response under defined conditions could be resolved it would be possible to predict the magnitude of evoked responses from the combination of the effective light intensity for each of the individual photoreceptors. For example, comparison of evoked responses to light with measures of effective light intensity under a variety of conditions could be used to reveal which photoreceptors dominate response amplitude. This requires a method of characterizing light that quantifies the input to each of the five known photoreceptor types. However, the spectral sensitivity function and new quantities and metrics to describe melanopsin-based photoreception are not yet defined. This standard provides these definitions so that the inputs of the five photoreceptor types that contribute to ipRGC-influenced responses can be characterized and used in relation to light, lighting and its effects on people, including its effects on health and well-being.

1 Scope

This International Standard defines spectral sensitivity functions, quantities and metrics to describe the ability of optical radiation to stimulate each of the five photoreceptor types that can contribute, via the melanopsin-containing intrinsically-photosensitive retinal ganglion cells (ipRGCs), to retina-mediated non-visual effects of light in humans. This International Standard is applicable to visible optical radiation in the wavelength range from 380 nm to 780 nm. In addition, this standard includes information concerning the effects of age and field of view (FOV) when quantifying retinal photoreceptor stimulation for ipRGC-influenced responses to light (IIL responses).

This International Standard does not give complete information for particular lighting applications, or for the quantitative prediction of IIL responses.

This International Standard is not intended for colorimetric contexts, nor does it address health or safety issues such as those resulting from light treatment, flicker or photobiological safety and only relates to retinal photoreception.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 23539/CIE S 010 *Photometry - The CIE system of physical photometry*.

CIE S 017 *ILV: International Lighting Vocabulary*.

[also accessible electronically as eILV at www.cie.co.at].

3 Terms and definitions

For the purposes of this document, in addition to the terms and definitions given in CIE S 017, the following terms and definitions apply.

3.1

α -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

Note 1 to entry: The prefix α in the term indicates one of five different photoreceptor responses, as set out in 3.1.1 to 3.1.5. The symbol α is also used to denote an index for quantity symbols related to these responses. Both these usages are summarized in Table 1.

3.1.1

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

Note 1 to entry: In this standard, S-cone-opic is based on the cone fundamental $\bar{s}_{10}(\lambda)$, as defined in (CIE, 2006). 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 (Lucas et al., 2014).

Note 2 to entry: The index “sc” is used for S-cone-opic quantities.

3.1.2

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

Note 1 to entry: In this standard, M-cone-opic is based on the cone fundamental $\bar{m}_{10}(\lambda)$, as defined in (CIE, 2006). 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 (Lucas et al., 2014).

Note 2 to entry: The index “mc” is used for M-cone-opic quantities.

3.1.3

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

Note 1 to entry: In this standard, L-cone-opic is based on the cone fundamental $\bar{l}_{10}(\lambda)$, as defined in (CIE, 2006). 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 (Lucas et al., 2014).

Note 2 to entry: The index “lc” is used for L-cone-opic quantities.

3.1.4

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

Note 1 to entry: In this standard, rhodopic is based on the sensitivity function $V'(\lambda)$ for scotopic vision, 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 (Lucas et al., 2014).

Note 2 to entry: The index “rh” is used for rhodopic quantities.

3.1.5

melanopic

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

Note 1 to entry: For the melanopic action spectrum $s_{\text{mel}}(\lambda)$ (see Definition 3.2) this standard uses the shape of the opsin-template-based melanopic spectral sensitivity function $N_z(\lambda)$ (Lucas et al., 2014).

Note 2 to entry: The index “mel” is used for melanopic quantities.

3.2

α -opic action spectrum

α -opic spectral weighting function

$s_{\alpha}(\lambda)$

function representing the relative spectral sensitivity of one of the five human α -opic photoreceptors to optical radiation incident at the cornea, normalized to have a maximum value of 1

Note 1 to entry: The α -opic action spectrum gives the ratio of radiant flux at a fixed reference wavelength λ_{ref} , to that at wavelength λ , such that both produce an equal photoreceptor activity attributable to the specified α -opic photoreceptor and λ_{ref} is chosen so that the maximum value of this ratio is equal to 1.

Note 2 to entry: The values of $s_{\alpha}(\lambda)$ for the five human photoreceptor responses are given in Table 2 and a plot of the values is given in Figure 1.

Note 3 to entry: The α -opic action spectrum has unit one.

3.3

α -opic radiant flux

$\Phi_{\text{e},\alpha}; \Phi_{\alpha}$

effective photobiological radiant flux with the spectral radiant flux, $\Phi_{\text{e},\lambda}(\lambda)$, spectrally weighted with the α -opic action spectrum, $s_{\alpha}(\lambda)$, expressed by

$$\Phi_{e,\alpha} = \int \Phi_{e,\lambda}(\lambda) s_{\alpha}(\lambda) d\lambda$$

Note 1 to entry: The optional first subscript "e" in the symbol denotes a radiometric quantity to distinguish from a photometric quantity such as α -opic equivalent daylight (D65) luminance, $L_{v,\alpha}^{D65}$, or α -opic equivalent daylight (D65) illuminance, $E_{v,\alpha}^{D65}$ (see Definitions 3.8 and 3.9). This notation convention also applies to other similar derived quantities such as radiant energy (expressed in J) and radiant intensity (expressed in W·sr⁻¹).

Note 2 to entry: α -opic radiant flux is expressed in watts (W).

3.4

α -opic efficacy of luminous radiation

$K_{\alpha,v}$

quotient of α -opic radiant flux, Φ_{α} , and luminous flux, Φ_v , expressed by

$$K_{\alpha,v} = \frac{\Phi_{\alpha}}{\Phi_v} = \frac{\int \Phi_{e,\lambda}(\lambda) s_{\alpha}(\lambda) d\lambda}{K_m \int \Phi_{e,\lambda}(\lambda) V(\lambda) d\lambda}$$

where $s_{\alpha}(\lambda)$ is one of the five α -opic action spectra, $V(\lambda)$ is the spectral luminous efficiency function for photopic vision, and K_m is the maximum spectral luminous efficacy of radiation for photopic vision, $K_m = 683,002 \text{ lm} \cdot \text{W}^{-1}$

Note 1 to entry: Luminous radiation refers to optical radiation over the wavelength range from 380 nm to 780 nm, weighted with the CIE spectral luminous efficiency function for photopic vision, $V(\lambda)$, as tabulated in ISO 23539/CIE S 010 for 1 nm increments.

Note 2 to entry: Unlike K_m , $K_{\alpha,v}$ depends on the spectrum of the optical radiation; it is not a constant (see Annex A.1). When presenting the numerical value of $K_{\alpha,v}$ for a light source, the light source must be stated.

Note 3 to entry: The abbreviated term " α -opic ELR" can be used to denote the α -opic efficacy of luminous radiation, $K_{\alpha,v}$. For example, in the case that α denotes melanopsin (index $\alpha=\text{mel}$), melanopic ELR denotes the melanopic efficacy of luminous radiation, $K_{\text{mel},v}$.

Note 4 to entry: α -opic efficacy of luminous radiation has the inverse units of K_m (see also (CIE, 2014)) and is expressed in watts per lumen ($\text{W} \cdot \text{lm}^{-1}$).

3.5

α -opic radiance, <in a given direction, at a given point of a real or imaginary surface>

$L_{e,\alpha}; L_{\alpha}$

effective photobiological radiance with the spectral radiance, $L_{e,\lambda}(\lambda)$, spectrally weighted with the α -opic action spectrum $s_{\alpha}(\lambda)$, expressed by

$$L_{e,\alpha} = \int L_{e,\lambda}(\lambda) s_{\alpha}(\lambda) d\lambda$$

Note 1 to entry: In ipRGC-influenced responses to light, the distribution of α -opic radiance across a field of view can be used to characterize the retinal α -opic stimulus, see Clause 5 and A.6. Moreover, the central direction and dimensions of the field of view usually also vary over time due to many factors including head and eye movements, eye-lid position and pupil constriction (see A.6).

Note 2 to entry: α -opic radiance is expressed in watts per square metre per steradian ($\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$).

3.6

α -opic irradiance, <at a point on a surface>

$E_{e,\alpha}; E_{\alpha}$

effective photobiological irradiance with the spectral irradiance, $E_{e,\lambda}(\lambda)$, spectrally weighted with the α -opic action spectrum $s_{\alpha}(\lambda)$, expressed by

$$E_{e,\alpha} = \int E_{e,\lambda}(\lambda) s_{\alpha}(\lambda) d\lambda$$

Note 1 to entry: The spectral irradiance at a point of a surface is the quotient of the spectral radiant flux incident on an element of the surface containing the point and the area of that element.

Note 2 to entry: α -opic irradiance is usually measured at the position of the outer surface of the eye in the outward direction of the optical axis of the eye (line of sight). Although measuring vertical α -opic irradiance at the position of the eye is common practice, Annex A.6 describes why this can sometimes be an over-simplification to quantify light for ipRGC-influenced responses to light (see Definition 3.12).

Note 3 to entry: α -opic irradiance is expressed in watts per square metre ($\text{W}\cdot\text{m}^{-2}$).

3.7

α -opic efficacy of luminous radiation for daylight (D65)

$$K_{\alpha,v}^{\text{D65}}$$

quotient of α -opic radiant flux of standard daylight (D65) and luminous flux of standard daylight (D65), expressed by

$$K_{\alpha,v}^{\text{D65}} = \frac{\Phi_{\alpha}^{\text{D65}}}{\Phi_v^{\text{D65}}}$$

Note 1 to entry: Luminous radiation refers to optical radiation over the wavelength range from 380 nm to 780 nm, weighted with the CIE spectral luminous efficiency function for photopic vision, $V(\lambda)$, as tabulated in ISO 23539/CIE S 010 for 1 nm increments.

Note 2 to entry: Standard daylight (D65) refers to the relative spectral power distribution representing a phase of daylight with a correlated colour temperature of approximately 6 500 K, as defined in CIE S 017.

Note 3 to entry: The five values of $K_{\alpha,v}^{\text{D65}}$ are:

$$K_{sc,v}^{\text{D65}} = 0,8173 \text{ mW}\cdot\text{lm}^{-1}$$

$$K_{mc,v}^{\text{D65}} = 1,4558 \text{ mW}\cdot\text{lm}^{-1}$$

$$K_{lc,v}^{\text{D65}} = 1,6289 \text{ mW}\cdot\text{lm}^{-1}$$

$$K_{rh,v}^{\text{D65}} = 1,4497 \text{ mW}\cdot\text{lm}^{-1}$$

$$K_{me,v}^{\text{D65}} = 1,3262 \text{ mW}\cdot\text{lm}^{-1}$$

Note 4 to entry: α -opic efficacy of luminous radiation for daylight (D65) is expressed in watts per lumen ($\text{W}\cdot\text{lm}^{-1}$).

3.8

α -opic equivalent daylight (D65) luminance, <in a given direction, at a given point of a real or imaginary surface>

$$L_{v,\alpha}^{\text{D65}}$$

luminance produced by radiation conforming to standard daylight (D65) that provides an equal α -opic radiance, L_{α} , as the test source, expressed by

$$L_{v,\alpha}^{\text{D65}} = \frac{L_{\alpha}}{K_{\alpha,v}^{\text{D65}}}$$

Note 1 to entry: An alternative way to calculate the α -opic equivalent daylight (D65) luminance is by using the α -opic daylight (D65) efficacy ratio, $\gamma_{\alpha,v}^{\text{D65}}$ (Definition 3.10), and the luminance, L_v , as follows: $L_{v,\alpha}^{\text{D65}} = L_v \cdot \gamma_{\alpha,v}^{\text{D65}}$

Note 2 to entry: In ipRGC-influenced responses to light, the distribution of α -opic equivalent daylight (D65) luminance across a field of view can be used to characterize the retinal α -opic stimulus, see Clause 5 and A.6. Moreover, the central direction and dimensions of the field of view usually also vary over time due to many factors including head and eye movements, eye-lid and pupil constriction (see A.6).

Note 3 to entry: Other α -opic equivalent daylight (D65) quantities (such as α -opic equivalent daylight (D65) luminous energy (unit $\text{lm}\cdot\text{s}$) and α -opic equivalent daylight (D65) luminous intensity (unit cd or $\text{lm}\cdot\text{sr}^{-1}$) can be calculated from the corresponding photometric quantities (respectively, luminous energy (unit $\text{lm}\cdot\text{s}$) and luminous intensity (unit cd or $\text{lm}\cdot\text{sr}^{-1}$)) in the same way as α -opic equivalent daylight (D65) luminance is calculated from luminance, see A.2 for details.

Note 4 to entry: Other reference spectra (e.g. the equi-energy spectrum) can also be used to define other α -opic equivalent luminances (e.g. the α -opic equivalent equi-energy (E) luminance, $L_{V,\alpha}^E$), in the same way as D65 is used in the current definition of α -opic equivalent daylight (D65) luminance, see A.3 for details. These alternatives can be considered for special situations and comparisons, but the D65 spectral distribution is recommended for use in the context of ipRGC-influenced responses to light.

Note 5 to entry: The abbreviated term " α -opic EDL" can be used to denote the α -opic equivalent daylight (D65) luminance, $L_{V,\alpha}^{D65}$. For example, in the case that α denotes melanopsin (index $\alpha=\text{mel}$), melanopic EDL denotes the melanopic equivalent daylight (D65) luminance, $L_{V,\text{mel}}^{D65}$.

Note 6 to entry: α -opic equivalent daylight (D65) luminance is expressed in candela per square metre ($\text{cd}\cdot\text{m}^{-2}$).

3.9

α -opic equivalent daylight (D65) illuminance, <at a point on a surface>

$$E_{V,\alpha}^{D65}$$

illuminance produced by radiation conforming to standard daylight (D65) that provides an equal α -opic irradiance, E_α , as the test source, expressed by

$$E_{V,\alpha}^{D65} = \frac{E_\alpha}{K_{\alpha,V}^{D65}}$$

Note 1 to entry: An alternative way to calculate the α -opic equivalent daylight (D65) illuminance is by using the α -opic daylight (D65) efficacy ratio (Definition 3.10) as follows: $E_{V,\alpha}^{D65} = E_V \cdot \gamma_{\alpha,V}^{D65}$

Note 2 to entry: α -opic equivalent daylight (D65) illuminance is usually measured at the position of the outer surface of the eye in the outward direction of the optical axis of the eye (line of sight). Although measuring vertical α -opic equivalent daylight (D65) illuminance at the position of the eye is common practice, A.6 describes why this can sometimes be an over-simplification to quantify light for ipRGC-influenced responses to light (see Definition 3.12).

Note 3 to entry: Other reference spectra (e.g. the equi-energy spectrum) can also be used to define other α -opic equivalent illuminances (e.g. the α -opic equivalent equi-energy (E) illuminance, $E_{V,\alpha}^E$), in the same way as D65 is used in the definition of α -opic equivalent daylight (D65) illuminance, see A.3 for details. These alternatives can be considered for special situations and comparisons, but the D65 spectral distribution is recommended for use in the context of ipRGC-influenced responses to light.

Note 4 to entry: The abbreviated term " α -opic EDI" can be used to denote the α -opic equivalent daylight (D65) illuminance, $E_{V,\alpha}^{D65}$. For example, in the case that α denotes melanopsin (index $\alpha=\text{mel}$), melanopic EDI denotes the melanopic equivalent daylight (D65) illuminance, $E_{V,\text{mel}}^{D65}$.

Note 5 to entry: α -opic equivalent daylight (D65) illuminance is expressed in lux (lx).

3.10

α -opic daylight (D65) efficacy ratio, <for a source>

$$\gamma_{\alpha,v}^{D65}$$

ratio of the α -opic efficacy of luminous radiation (for a source), $K_{\alpha,v}$, to the α -opic efficacy of luminous radiation for daylight (D65), $K_{\alpha,v}^{D65}$, expressed by

$$\gamma_{\alpha,v}^{D65} = \frac{K_{\alpha,v}}{K_{\alpha,v}^{D65}} = \frac{\Phi_{\alpha} / \Phi_v}{\Phi_{\alpha}^{D65} / \Phi_v^{D65}}$$

Note 1 to entry: The α -opic equivalent daylight (D65) illuminance is the product of the photopic illuminance produced by optical radiation and the α -opic daylight (D65) efficacy ratio, $\gamma_{\alpha,v}^{D65}$, of this optical radiation. Similarly, the α -opic equivalent daylight (D65) luminance is the product of the photopic luminance produced by optical radiation and the α -opic daylight (D65) efficacy ratio, $\gamma_{\alpha,v}^{D65}$, of this optical radiation.

Note 2 to entry: The abbreviated term " α -opic DER" can be used to denote the α -opic daylight (D65) efficacy ratio, $\gamma_{\alpha,v}^{D65}$. For example, in the case that α denotes melanopsin (index $\alpha=\text{mel}$), melanopic DER denotes the melanopic daylight (D65) efficacy ratio, $\gamma_{\text{mel},v}^{D65}$.

Note 3 to entry: The five values of $K_{\alpha,v}^{D65}$ are:

$$K_{\text{sc},v}^{D65} = 0,8173 \text{ mW} \cdot \text{lm}^{-1}$$

$$K_{\text{mc},v}^{D65} = 1,4558 \text{ mW} \cdot \text{lm}^{-1}$$

$$K_{\text{lc},v}^{D65} = 1,6289 \text{ mW} \cdot \text{lm}^{-1}$$

$$K_{\text{rh},v}^{D65} = 1,4497 \text{ mW} \cdot \text{lm}^{-1}$$

$$K_{\text{mel},v}^{D65} = 1,3262 \text{ mW} \cdot \text{lm}^{-1}$$

Note 4 to entry: α -opic daylight (D65) efficacy ratio has unit one.

3.11

ipRGCs

intrinsically-photosensitive retinal ganglion cells

retinal ganglion cells that are photosensitive by means of the photopigment melanopsin

Note 1 to entry: ipRGCs receive signals from rods and cones and hence combine the photoreceptive contributions from all five α -opic photopigments. However, melanopsin is the only known photopigment that occurs within ipRGCs themselves, thus accounting for the intrinsic photosensitivity of the ipRGCs.

Note 2 to entry: ipRGCs are sometimes denoted as photosensitive retinal ganglion cells (pRGCs), or melanopsin-expressing retinal ganglion cells, or melanopsin-containing retinal ganglion cells.

3.12

ipRGC-influenced responses to light

ipRGC-influenced light responses

IIL responses

light-induced responses or effects that can be elicited by ipRGCs

Note 1 to entry: ipRGCs may play a role in both visual and non-visual responses to ocular light exposure. At present ipRGC-influenced responses to light are often referred to as non-image-forming (NIF) or non-visual (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 we gain more knowledge.

Note 2 to entry: ipRGC-influenced responses to light may be influenced by rod, cone and melanopsin inputs.