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Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

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.

Contents

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 $s_{\mathrm{mel}}(\lambda)$ (see Definition 3.2) this standard uses the shape of the opsin-template-based melanopic spectral sensitivity function $N_{\mathrm{z}}(\lambda)$ (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
$\Phi_{\mathrm{e},\alpha}$; Φ_{α}
effective photobiological radiant flux with the spectral radiant flux, $\Phi_{\mathrm{e},\lambda}(\lambda)$, spectrally weighted with the α-opic action spectrum, $s_{\alpha}(\lambda)$, expressed by

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

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, $L_{\mathrm{v},\alpha}^{\mathrm{D65}}$, or α-opic equivalent daylight (D65) illuminance, $E_{\mathrm{v},\alpha}^{\mathrm{D65}}$ (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

$K_{\alpha,\mathrm{v}}$

quotient of α-opic radiant flux, Φ_α, and luminous flux, Φ_v, expressed by

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

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 lm·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, $K_{\alpha,\mathrm{v}}$ depends on the spectrum of the optical radiation; it is not a constant (see Annex A.1). When presenting the numerical value of $K_{\alpha,\mathrm{v}}$ 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, $K_{\alpha,\mathrm{v}}$. For example, in the case that α denotes melanopsin (index α=mel), melanopic ELR denotes the melanopic efficacy of luminous radiation, $K_{mel,\,\mathrm{v}}$.

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 (W·lm^{-1}).

3.5
α-opic radiance, <in a given direction, at a given point of a real or imaginary surface>

$L_{\mathrm{e},\alpha}$; L_α

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

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

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 (W·m^{-2}·sr^{-1}).

3.6
α-opic irradiance, <at a point on a surface>

$E_{\mathrm{e},\alpha}$; E_α

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

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

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 ($\mathrm{W{\cdot}m^{-2}}$).

3.7
α-opic efficacy of luminous radiation for daylight (D65)

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

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

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

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 $K_{\alpha,\mathrm{v}}^{\mathrm{D65}}$ are:

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

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

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

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

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

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

3.8
α-opic equivalent daylight (D65) luminance, <in a given direction, at a given point of a real or imaginary surface>

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

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

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

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, $\gamma_{\alpha,\mathrm{v}}^{\mathrm{D65}}$ (Definition 3.10), and the luminance, L_v, as follows: $L_{\mathrm{v},\alpha}^{\mathrm{D65}} = L_\mathrm{v} \cdot \gamma_{\alpha,\mathrm{v}}^{\mathrm{D65}}$

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 lm·s)) and α-opic equivalent daylight (D65) luminous intensity (unit cd or $\mathrm{lm \cdot sr^{-1}}$) can be calculated from the corresponding photometric quantities (respectively, luminous energy (unit lm·s) and luminous intensity (unit cd or $\mathrm{lm \cdot sr^{-1}}$)) 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, $L_{\mathrm{v},\alpha}^{\mathrm{E}}$), 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, $L_{\mathrm{v},\alpha}^{\mathrm{D65}}$. For example, in the case that α denotes melanopsin (index α=mel), melanopic EDL denotes the melanopic equivalent daylight (D65) luminance, $L_{\mathrm{v,mel}}^{\mathrm{D65}}$.

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

3.9

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

$E_{\mathrm{v},\alpha}^{\mathrm{D65}}$

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

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

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: $E_{\mathrm{v},\alpha}^{\mathrm{D65}} = E_{\mathrm{v}} \cdot \gamma_{\alpha,\mathrm{v}}^{\mathrm{D65}}$

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, $E_{\mathrm{v},\alpha}^{\mathrm{E}}$), 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, $E_{\mathrm{v},\alpha}^{\mathrm{D65}}$. For example, in the case that α denotes melanopsin (index α=mel), melanopic EDI denotes the melanopic equivalent daylight (D65) illuminance, $E_{\mathrm{v,mel}}^{\mathrm{D65}}$.

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

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

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

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, $\gamma_{\alpha,\mathrm{v}}^{\mathrm{D65}}$, 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, $\gamma_{\alpha,\mathrm{v}}^{\mathrm{D65}}$, 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, $\gamma_{\alpha,\mathrm{v}}^{\mathrm{D65}}$. For example, in the case that α denotes melanopsin (index α=mel), melanopic DER denotes the melanopic daylight (D65) efficacy ratio, $\gamma_{\mathrm{mel,v}}^{\mathrm{D65}}$.

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

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

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

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

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

$K_{\mathrm{mel,v}}^{\mathrm{D65}}$ = 1,3262 mW·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.

4 Action spectra for human photoreception

4.1 Scientific background

All five known photoreceptors in the extra-foveal and peripheral retina of the human eye – three cone classes, rods and melanopsin-containing intrinsically photosensitive retinal ganglion cells known as ipRGCs – can contribute to IIL responses (Lucas et al., 2014). The Lucas et al. authors produced five action spectra for the five photoreceptors and their respective photopigments, using an opsin template and an adapted lens transmittance function. Of these, the melanopic action spectrum is the most widely used by researchers and lighting practitioners.

4.2 Cone sensitivities

CIE already has a comprehensive publication (CIE, 2006) for the photoreceptive properties of the three cone classes. The differences between the cone sensitivity functions published by Lucas et al. (2014) and CIE (2006) are not considered significant when considering IIL responses, as these differences are no greater than the natural variations between healthy individuals of the same age. Therefore this standard uses the published CIE cone sensitivities.

The photoreceptors that can contribute to IIL responses are located in the extra-foveal and peripheral retina, which relates to a field size of 10° or more. In this standard the 10° observer is taken as being representative of extra-foveal cone function for the cones which influence ipRGC responses, for which the influence of the macular pigment is negligible.

4.3 Rod sensitivity

CIE has a standard for the photoreceptive properties of the scotopic response to light, which is entirely based on photoreception by the rods (ISO 23539/CIE S 010). This is well known as the scotopic luminous efficiency function, $V'(\lambda)$. For the same reason as in 4.2, the differences between the rhodopic function according to Lucas et al. (2014) and $V'(\lambda)$ are not considered significant when considering IIL responses, and therefore this standard uses the latter.

As rods are located in the extra-foveal and peripheral retina, $V'(\lambda)$ is consistent with the retinal field applicable for IIL responses.

4.4 ipRGC (melanopic) sensitivity

Unlike rod and cone photoreceptors, melanopsin photoreception has no well-established psychophysical assessment methods with which to define its action spectrum. Several lines of evidence provide confidence that the melanopic action spectrum employed here is appropriate (see A.4). From these, a consensus has developed that the action spectrum of human melanopsin can be approximated by that of an (opsin:vitamin A)-based photopigment template with a peak around 480 nm, and that the sensitivity of melanopsin photoreception in vivo can then be derived by including an adjustment to account for pre-receptoral filtering, see A.4, (Lucas et al., 2014) and (CIE, 2015).

4.5 ipRGC-influenced responses to light

The approach of this CIE standard is to provide standard action spectra for all five known photoreceptors in the extra-foveal and peripheral retina of the human eye, relating to their contribution to IIL responses.

To ensure that the standard does not create contradictory standards within CIE, this standard defines five action spectra for light assessments, using the rod and cone sensitivity functions from the existing CIE publications, together with a widely agreed melanopic sensitivity function (full details are provided in NOTE 1 to Table 2):

- the three CIE cone sensitivity functions for the 10° observer (cone fundamentals) (CIE, 2006);
- the CIE scotopic sensitivity function for rods (ISO 23539/CIE S 010);
- the Lucas et al. melanopic sensitivity function (Lucas et al., 2014).

The five action spectra are plotted in Figure 1 and tabulated in steps of 1 nm in Table 2. The values are also available at http://files.cie.co.at/S026_Table2_Data.xlsx.

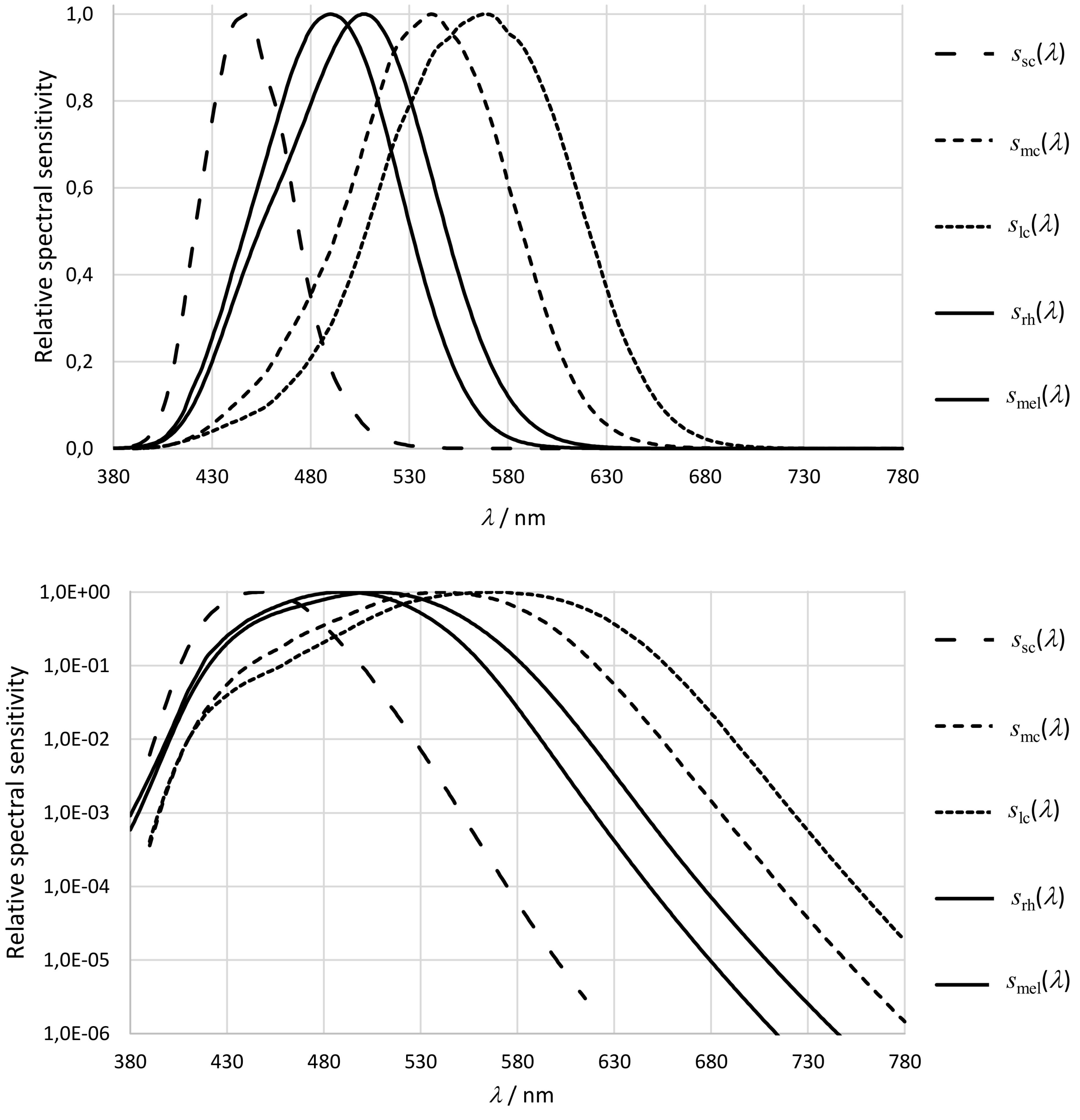

Figure 1 — The five α-opic action spectra as given in Table 2, $s_{sc}(\lambda)$, $s_{mc}(\lambda)$, $s_{lc}(\lambda)$, $s_{rh}(\lambda)$ and $s_{mel}(\lambda)$ respectively, plotted against wavelength, λ, using a linear (top) and logarithmic (bottom) scale for the relative spectral sensitivity

4.6 Pre-receptoral filtering and age

The human ocular lens becomes more yellow and less transparent with age, and there are large inter-individual differences in this ageing process (Mellerio, 1987). Information about a possible method to address differences in pre-receptoral filtering due to age is set out in A.5.

5 Field of view

In addition to spectral information, the determination of spatial variations can also be important for IIL responses, since the ocular FOV, particularly in the vertical dimension, varies greatly with gaze angle and ambient luminance (Deaver et al., 1996; Sliney, 2002). Since there are large differences amongst individuals in these FOV variations (Deaver et al., 1996), it is not possible to define a fixed FOV. Instead, non-normative information regarding a possible method to address the measurement aspects related to the FOV is set out in A.6.

The standard radiometric or photometric quantities that directly relate to retinal irradiance or retinal illuminance are respectively the radiance and luminance of the field actually being viewed[1]. For the Gullstrand schematic eye, the retinal illuminance (or irradiance), E_{retina}, is directly proportional to the luminance (or radiance), L, for a pupil diameter d (in cm) by:

$$E_{\text{retina}} = \frac{\pi\, L\, \tau\, d^2}{4\, f^2} \approx (0{,}27\ \text{cm}^{-2})\, L\, \tau\, d^2 \qquad (1)$$

where τ is the transmittance of the ocular media, f = 1,7 cm is the effective focal length in air of the Gullstrand eye (ICNIRP, 2013; Sliney and Wolbarsht, 1980). For stimuli imaged far in the peripheral retina, the retinal illuminance calculation by Equation (1) may require an extra correction for variation in the effective pupillary area.

As the α-opic weighting functions include a correction for pre-receptoral filtering, for α-opic quantities Equation (1) must be applied without the transmittance term τ

$$E_{\alpha,\text{retina}} = \frac{\pi\, L_\alpha\, d^2}{4\, f^2} \approx (0{,}27\ \text{cm}^{-2})\, L_\alpha\, d^2 \qquad (2)$$

where L_α represents α-opic radiance and $E_{\alpha,\text{retina}}$ is the associated α-opic irradiance.

Similarly the following formula holds for α-opic equivalent daylight (D65) quantities:

$$E_{\alpha,\text{retina}}^{\text{D65}} = \frac{\pi\, L_\alpha^{\text{D65}}\, d^2}{4\, f^2} \approx (0{,}27\ \text{cm}^{-2})\, L_\alpha^{\text{D65}}\, d^2 \qquad (3)$$

Many light sources and scenes show significant spatial variations in radiance over their surface and in this case it is not appropriate to use a single radiance measure when considering IIL responses. Two very different radiance distributions can give rise to the same average corneal irradiance, but may or may not have the same effect on the IIL responses. It is also important to note that when the radiance is averaged over a given FOV (see A.6), Equations (1) to (3) provide the spatially averaged retinal irradiance over the corresponding image area. In order to calculate a localized retinal irradiance (which may be more important in terms of the IIL responses) a smaller measurement FOV must be used.

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1 The troland (Td) has historically been used in the visual sciences as a unit to express conventional retinal illuminance. The unit troland by itself is not an SI unit, it expresses conventional retinal illuminance by multiplying the luminance in $\text{cd}\cdot\text{m}^{-2}$ with the pupil area in mm^2. Note that when quoting results of α-opic quantities in Td, it is important to also state the weighting function used, since the unit is the same in all cases.

6 Tables

Table 1 — Terminology and notation of the CIE system for metrology of optical radiation for ipRGC-influenced responses to light (IIL responses)

Response	Index α	Photoreceptor	Photopigment	α-opic action spectrum, $s_\alpha(\lambda)$	α-opic irradiance, E_α ($W \cdot m^{-2}$)	α-opic equivalent daylight (D65) illuminance, $E_{v,\alpha}$ (lx)
S-cone-opic	sc	Short-wavelength cones	S-cone photopsin (cyanolabe)	$s_{sc}(\lambda)$	E_{sc}	$E_{v,sc}$
M-cone-opic	mc	Medium-wavelength cones	M-cone photopsin (chlorolabe)	$s_{mc}(\lambda)$	E_{mc}	$E_{v,mc}$
L-cone-opic	lc	Long-wavelength cones	L-cone photopsin (erythrolabe)	$s_{lc}(\lambda)$	E_{lc}	$E_{v,lc}$
Rhodopic	rh	Rods	Rhodopsin	$s_{rh}(\lambda)$	E_{rh}	$E_{v,rh}$
Melanopic	mel	ipRGCs	Melanopsin	$s_{mel}(\lambda)$	E_{mel}	$E_{v,mel}$

NOTE In this standard, the values of the S-cone-opic, M-cone-opic and L-cone-opic action spectra are based on the 10° cone fundamentals from (CIE, 2006). This differs from the approach in (Lucas et al., 2014) where the human cone responses are denoted by the analogous terms “cyanopic”, “chloropic” and “erythropic” respectively, and where their spectral sensitivity functions are based on an opsin template (Govardovskii et al., 2000; CIE, 2015).

Table 2 — Values of the α-opic action spectra

λ (nm)	S-cone-opic $s_{sc}(\lambda)$	M-cone-opic $s_{mc}(\lambda)$	L-cone-opic $s_{lc}(\lambda)$	rhodopic $s_{rh}(\lambda)$	melanopic $s_{mel}(\lambda)$
380				5,89E−04	9,181 65E−04
381				6,65E−04	1,045 57E−03
382				7,52E−04	1,178 58E−03
383				8,54E−04	1,322 79E−03
384				9,72E−04	1,483 81E−03
385				1,108E−03	1,667 24E−03
386				1,268E−03	1,881 02E−03
387				1,453E−03	2,129 89E−03
388				1,668E−03	2,414 57E−03
389				1,918E−03	2,735 83E−03
390	6,142 65E−03	3,582 27E−04	4,076 19E−04	2,209E−03	3,094 42E−03
391	7,442 80E−03	4,386 60E−04	4,970 68E−04	2,547E−03	3,507 06E−03
392	9,016 61E−03	5,362 30E−04	6,047 13E−04	2,939E−03	3,990 78E−03
393	1,091 70E−02	6,540 61E−04	7,336 40E−04	3,394E−03	4,546 79E−03
394	1,320 53E−02	7,956 49E−04	8,872 47E−04	3,921E−03	5,176 25E−03
395	1,595 15E−02	9,648 28E−04	1,069 21E−03	4,53E−03	5,880 35E−03
396	1,923 47E−02	1,165 72E−03	1,283 40E−03	5,24E−03	6,693 34E−03
397	2,314 36E−02	1,402 63E−03	1,533 82E−03	6,05E−03	7,651 02E−03
398	2,777 50E−02	1,679 92E−03	1,824 43E−03	6,98E−03	8,756 94E−03
399	3,323 39E−02	2,001 80E−03	2,158 96E−03	8,06E−03	1,001 46E−02
400	3,963 08E−02	2,372 08E−03	2,540 73E−03	9,29E−03	1,142 77E−02
401	4,708 01E−02	2,794 33E−03	2,972 82E−03	1,070E−02	1,307 67E−02
402	5,570 12E−02	3,273 74E−03	3,459 93E−03	1,231E−02	1,503 97E−02
403	6,561 37E−02	3,816 60E−03	4,007 93E−03	1,413E−02	1,731 66E−02
404	7,693 23E−02	4,430 21E−03	4,623 70E−03	1,619E−02	1,990 71E−02
405	8,976 12E−02	5,123 16E−03	5,315 46E−03	1,852E−02	2,281 12E−02
406	1,041 88E−01	5,904 58E−03	6,091 38E−03	2,113E−02	2,631 94E−02
407	1,202 73E−01	6,780 05E−03	6,952 91E−03	2,405E−02	3,059 64E−02
408	1,380 44E−01	7,752 60E−03	7,896 34E−03	2,730E−02	3,545 38E−02
409	1,574 85E−01	8,822 86E−03	8,913 00E−03	3,089E−02	4,070 28E−02
410	1,785 30E−01	9,988 41E−03	9,988 35E−03	3,484E−02	4,615 50E−02
411	2,010 77E−01	1,124 52E−02	1,110 54E−02	3,916E−02	5,178 22E−02
412	2,250 91E−01	1,259 49E−02	1,226 07E−02	4,39E−02	5,778 04E−02
413	2,505 66E−01	1,404 25E−02	1,345 78E−02	4,90E−02	6,429 72E−02
414	2,775 07E−01	1,559 44E−02	1,470 44E−02	5,45E−02	7,148 01E−02
415	3,059 41E−01	1,725 96E−02	1,601 30E−02	6,04E−02	7,947 66E−02
416	3,358 58E−01	1,904 67E−02	1,739 58E−02	6,68E−02	8,918 07E−02
417	3,669 81E−01	2,095 45E−02	1,884 52E−02	7,36E−02	1,007 56E−01
418	3,988 76E−01	2,297 63E−02	2,034 40E−02	8,08E−02	1,132 56E−01
419	4,309 98E−01	2,510 17E−02	2,187 00E−02	8,85E−02	1,257 32E−01
420	4,626 92E−01	2,731 63E−02	2,339 57E−02	9,66E−02	1,372 37E−01
421	4,933 57E−01	2,960 62E−02	2,489 61E−02	1,052E−01	1,474 46E−01
422	5,230 06E−01	3,197 46E−02	2,637 61E−02	1,141E−01	1,570 14E−01
423	5,519 39E−01	3,443 30E−02	2,785 41E−02	1,235E−01	1,664 63E−01

Table 2 — Continued

λ (nm)	S-cone-opic $s_{sc}(\lambda)$	M-cone-opic $s_{mc}(\lambda)$	L-cone-opic $s_{lc}(\lambda)$	rhodopic $s_{rh}(\lambda)$	melanopic $s_{mel}(\lambda)$
424	5,805 99E−01	3,699 83E−02	2,935 51E−02	1,334E−01	1,763 16E−01
425	6,095 70E−01	3,969 28E−02	3,091 04E−02	1,436E−01	1,870 96E−01
426	6,393 59E−01	4,254 02E−02	3,254 98E−02	1,541E−01	1,992 10E−01
427	6,696 51E−01	4,554 74E−02	3,427 14E−02	1,651E−01	2,124 08E−01
428	6,998 29E−01	4,871 61E−02	3,606 20E−02	1,764E−01	2,262 25E−01
429	7,291 77E−01	5,204 67E−02	3,790 52E−02	1,879E−01	2,401 99E−01
430	7,568 85E−01	5,553 84E−02	3,978 10E−02	1,998E−01	2,538 65E−01
431	7,822 92E−01	5,918 76E−02	4,167 05E−02	2,119E−01	2,670 21E−01
432	8,056 66E−01	6,298 19E−02	4,357 28E−02	2,243E−01	2,799 76E−01
433	8,275 99E−01	6,690 31E−02	4,549 32E−02	2,369E−01	2,930 34E−01
434	8,487 80E−01	7,092 85E−02	4,743 85E−02	2,496E−01	3,065 00E−01
435	8,699 84E−01	7,502 99E−02	4,941 72E−02	2,625E−01	3,206 79E−01
436	8,917 61E−01	7,917 69E−02	5,143 43E−02	2,755E−01	3,360 16E−01
437	9,134 44E−01	8,334 63E−02	5,347 35E−02	2,886E−01	3,523 61E−01
438	9,339 77E−01	8,751 60E−02	5,551 02E−02	3,017E−01	3,691 28E−01
439	9,522 18E−01	9,166 25E−02	5,751 66E−02	3,149E−01	3,857 32E−01
440	9,669 60E−01	9,576 12E−02	5,946 19E−02	3,281E−01	4,015 87E−01
441	9,773 40E−01	9,979 77E−02	6,132 40E−02	3,412E−01	4,164 72E−01
442	9,840 28E−01	1,038 04E−01	6,312 88E−02	3,543E−01	4,307 97E−01
443	9,881 44E−01	1,078 34E−01	6,491 89E−02	3,673E−01	4,449 21E−01
444	9,908 51E−01	1,119 48E−01	6,674 25E−02	3,803E−01	4,592 03E−01
445	9,933 36E−01	1,162 20E−01	6,865 38E−02	3,931E−01	4,740 02E−01
446	9,963 73E−01	1,207 06E−01	7,069 63E−02	4,06E−01	4,895 17E−01
447	9,990 38E−01	1,253 63E−01	7,285 08E−02	4,18E−01	5,055 22E−01
448	9,999 78E−01	1,301 11E−01	7,507 78E−02	4,31E−01	5,217 41E−01
449	9,978 44E−01	1,348 56E−01	7,733 25E−02	4,43E−01	5,378 98E−01
450	9,913 29E−01	1,394 93E−01	7,956 47E−02	4,55E−01	5,537 15E−01
451	9,796 57E−01	1,439 43E−01	8,173 68E−02	4,67E−01	5,691 00E−01
452	9,639 05E−01	1,482 81E−01	8,388 26E−02	4,79E−01	5,842 40E−01
453	9,455 73E−01	1,526 37E−01	8,605 98E−02	4,90E−01	5,992 81E−01
454	9,260 78E−01	1,571 57E−01	8,833 22E−02	5,02E−01	6,143 70E−01
455	9,067 35E−01	1,620 06E−01	9,077 04E−02	5,13E−01	6,296 54E−01
456	8,885 09E−01	1,673 31E−01	9,343 97E−02	5,24E−01	6,451 93E−01
457	8,713 53E−01	1,731 44E−01	9,635 77E−02	5,35E−01	6,608 92E−01
458	8,549 98E−01	1,794 17E−01	9,953 04E−02	5,46E−01	6,766 60E−01
459	8,391 98E−01	1,861 17E−01	1,029 64E−01	5,57E−01	6,924 09E−01
460	8,237 26E−01	1,932 02E−01	1,066 63E−01	5,67E−01	7,080 49E−01
461	8,083 07E−01	2,006 21E−01	1,106 29E−01	5,78E−01	7,235 94E−01
462	7,924 31E−01	2,083 15E−01	1,148 28E−01	5,88E−01	7,391 05E−01
463	7,755 69E−01	2,162 12E−01	1,192 17E−01	5,99E−01	7,545 60E−01
464	7,572 44E−01	2,242 31E−01	1,237 40E−01	6,10E−01	7,699 38E−01
465	7,370 43E−01	2,322 75E−01	1,283 36E−01	6,20E−01	7,852 16E−01
466	7,147 30E−01	2,402 57E−01	1,329 47E−01	6,31E−01	8,006 83E−01
467	6,905 58E−01	2,481 60E−01	1,375 70E−01	6,42E−01	8,163 54E−01

Table 2 — Continued

λ (nm)	S-cone-opic $s_{sc}(\lambda)$	M-cone-opic $s_{mc}(\lambda)$	L-cone-opic $s_{lc}(\lambda)$	rhodopic $s_{rh}(\lambda)$	melanopic $s_{mel}(\lambda)$
468	6,648 90E−01	2,559 87E−01	1,422 18E−01	6,53E−01	8,317 98E−01
469	6,380 78E−01	2,637 44E−01	1,469 05E−01	6,64E−01	8,465 87E−01
470	6,104 56E−01	2,714 41E−01	1,516 51E−01	6,76E−01	8,602 91E−01
471	5,823 46E−01	2,790 97E−01	1,564 75E−01	6,87E−01	8,729 25E−01
472	5,540 65E−01	2,867 55E−01	1,614 04E−01	6,99E−01	8,848 70E−01
473	5,259 03E−01	2,944 76E−01	1,664 64E−01	7,10E−01	8,962 42E−01
474	4,981 08E−01	3,023 23E−01	1,716 90E−01	7,22E−01	9,071 58E−01
475	4,708 94E−01	3,103 72E−01	1,771 16E−01	7,34E−01	9,177 34E−01
476	4,444 50E−01	3,186 92E−01	1,827 77E−01	7,45E−01	9,283 45E−01
477	4,189 92E−01	3,273 07E−01	1,886 85E−01	7,57E−01	9,389 50E−01
478	3,946 99E−01	3,362 32E−01	1,948 45E−01	7,69E−01	9,490 35E−01
479	3,717 07E−01	3,454 80E−01	2,012 61E−01	7,81E−01	9,580 91E−01
480	3,501 08E−01	3,550 66E−01	2,079 40E−01	7,93E−01	9,656 05E−01
481	3,299 04E−01	3,649 85E−01	2,148 75E−01	8,05E−01	9,719 76E−01
482	3,108 64E−01	3,751 42E−01	2,220 22E−01	8,17E−01	9,778 33E−01
483	2,927 41E−01	3,854 10E−01	2,293 16E−01	8,28E−01	9,830 06E−01
484	2,753 38E−01	3,956 46E−01	2,366 84E−01	8,40E−01	9,873 25E−01
485	2,584 97E−01	4,056 88E−01	2,440 46E−01	8,51E−01	9,906 21E−01
486	2,421 58E−01	4,154 35E−01	2,513 47E−01	8,62E−01	9,933 43E−01
487	2,265 04E−01	4,250 64E−01	2,586 95E−01	8,73E−01	9,958 87E−01
488	2,117 26E−01	4,348 51E−01	2,662 52E−01	8,84E−01	9,980 08E−01
489	1,979 60E−01	4,450 97E−01	2,742 02E−01	8,94E−01	9,994 61E−01
490	1,852 97E−01	4,561 37E−01	2,827 52E−01	9,04E−01	1,000 00E+00
491	1,737 51E−01	4,682 36E−01	2,920 71E−01	9,14E−01	9,995 61E−01
492	1,631 49E−01	4,812 55E−01	3,020 94E−01	9,23E−01	9,983 65E−01
493	1,533 11E−01	4,949 27E−01	3,126 73E−01	9,32E−01	9,965 90E−01
494	1,440 86E−01	5,089 47E−01	3,236 37E−01	9,41E−01	9,944 16E−01
495	1,353 51E−01	5,229 70E−01	3,347 86E−01	9,49E−01	9,920 22E−01
496	1,270 11E−01	5,367 01E−01	3,459 43E−01	9,57E−01	9,887 92E−01
497	1,190 17E−01	5,501 95E−01	3,571 26E−01	9,64E−01	9,842 20E−01
498	1,113 33E−01	5,636 16E−01	3,684 16E−01	9,70E−01	9,786 57E−01
499	1,039 34E−01	5,771 50E−01	3,799 07E−01	9,76E−01	9,724 51E−01
500	9,679 90E−02	5,910 03E−01	3,917 05E−01	9,82E−01	9,659 52E−01
501	8,991 69E−02	6,053 50E−01	4,039 05E−01	9,86E−01	9,588 44E−01
502	8,328 78E−02	6,201 60E−01	4,165 00E−01	9,90E−01	9,507 16E−01
503	7,691 57E−02	6,353 43E−01	4,294 53E−01	9,94E−01	9,417 78E−01
504	7,080 52E−02	6,507 96E−01	4,427 20E−01	9,97E−01	9,322 36E−01
505	6,496 14E−02	6,664 04E−01	4,562 52E−01	9,98E−01	9,222 99E−01
506	5,940 49E−02	6,820 55E−01	4,699 97E−01	1,000E+00	9,118 32E−01
507	5,420 76E−02	6,976 72E−01	4,839 26E−01	1,000E+00	9,006 02E−01
508	4,942 81E−02	7,131 86E−01	4,980 12E−01	1,000E+00	8,886 63E−01
509	4,509 93E−02	7,285 26E−01	5,122 27E−01	9,98E−01	8,760 73E−01
510	4,123 37E−02	7,436 12E−01	5,265 38E−01	9,97E−01	8,628 88E−01
511	3,781 42E−02	7,583 96E−01	5,409 23E−01	9,94E−01	8,488 01E−01

Table 2 — Continued

λ (nm)	S-cone-opic $s_{sc}(\lambda)$	M-cone-opic $s_{mc}(\lambda)$	L-cone-opic $s_{lc}(\lambda)$	rhodopic $s_{rh}(\lambda)$	melanopic $s_{mel}(\lambda)$
512	3,476 27E−02	7,729 66E−01	5,554 06E−01	9,90E−01	8,336 78E−01
513	3,200 29E−02	7,874 57E−01	5,700 25E−01	9,86E−01	8,178 32E−01
514	2,947 46E−02	8,020 17E−01	5,848 28E−01	9,81E−01	8,015 79E−01
515	2,713 00E−02	8,168 08E−01	5,998 67E−01	9,75E−01	7,852 33E−01
516	2,493 76E−02	8,319 19E−01	6,151 62E−01	9,68E−01	7,687 18E−01
517	2,289 31E−02	8,470 96E−01	6,305 69E−01	9,61E−01	7,518 07E−01
518	2,099 56E−02	8,619 72E−01	6,458 83E−01	9,53E−01	7,345 93E−01
519	1,924 27E−02	8,761 52E−01	6,608 80E−01	9,44E−01	7,171 69E−01
520	1,762 98E−02	8,892 14E−01	6,753 13E−01	9,35E−01	6,996 28E−01
521	1,615 01E−02	9,008 12E−01	6,889 75E−01	9,25E−01	6,818 88E−01
522	1,479 11E−02	9,110 06E−01	7,018 86E−01	9,15E−01	6,638 81E−01
523	1,354 07E−02	9,199 68E−01	7,141 40E−01	9,04E−01	6,457 24E−01
524	1,238 84E−02	9,278 90E−01	7,258 41E−01	8,92E−01	6,275 33E−01
525	1,132 52E−02	9,349 77E−01	7,371 08E−01	8,80E−01	6,094 22E−01
526	1,034 37E−02	9,414 14E−01	7,480 46E−01	8,67E−01	5,913 39E−01
527	9,440 92E−03	9,472 79E−01	7,586 84E−01	8,54E−01	5,732 07E−01
528	8,613 65E−03	9,526 22E−01	7,690 32E−01	8,40E−01	5,551 05E−01
529	7,858 31E−03	9,574 98E−01	7,790 99E−01	8,26E−01	5,371 12E−01
530	7,170 89E−03	9,619 62E−01	7,889 00E−01	8,11E−01	5,193 09E−01
531	6,546 48E−03	9,660 80E−01	7,984 72E−01	7,96E−01	5,016 45E−01
532	5,977 77E−03	9,699 66E−01	8,079 45E−01	7,81E−01	4,840 67E−01
533	5,457 94E−03	9,737 43E−01	8,174 78E−01	7,65E−01	4,666 43E−01
534	4,981 25E−03	9,775 39E−01	8,272 39E−01	7,49E−01	4,494 42E−01
535	4,542 87E−03	9,814 81E−01	8,374 03E−01	7,33E−01	4,325 33E−01
536	4,139 08E−03	9,856 29E−01	8,480 78E−01	7,17E−01	4,158 62E−01
537	3,767 94E−03	9,897 54E−01	8,590 64E−01	7,00E−01	3,993 72E−01
538	3,427 83E−03	9,935 51E−01	8,700 68E−01	6,83E−01	3,831 36E−01
539	3,116 96E−03	9,967 14E−01	8,807 79E−01	6,67E−01	3,672 24E−01
540	2,833 52E−03	9,989 31E−01	8,908 71E−01	6,50E−01	3,517 07E−01
541	2,575 56E−03	9,999 42E−01	9,000 57E−01	6,33E−01	3,365 37E−01
542	2,340 84E−03	9,996 92E−01	9,082 53E−01	6,16E−01	3,216 47E−01
543	2,127 22E−03	9,981 78E−01	9,154 33E−01	5,99E−01	3,070 85E−01
544	1,932 76E−03	9,954 05E−01	9,215 75E−01	5,81E−01	2,928 99E−01
545	1,755 73E−03	9,913 83E−01	9,266 60E−01	5,64E−01	2,791 35E−01
546	1,594 55E−03	9,861 99E−01	9,307 44E−01	5,48E−01	2,657 37E−01
547	1,447 83E−03	9,802 29E−01	9,341 60E−01	5,31E−01	2,526 48E−01
548	1,314 30E−03	9,739 06E−01	9,373 18E−01	5,14E−01	2,399 17E−01
549	1,192 81E−03	9,676 53E−01	9,406 34E−01	4,97E−01	2,275 92E−01
550	1,082 30E−03	9,618 76E−01	9,445 27E−01	4,81E−01	2,157 22E−01
551	9,818 19E−04	9,568 20E−01	9,492 91E−01	4,65E−01	2,042 38E−01
552	8,905 33E−04	9,521 51E−01	9,546 80E−01	4,48E−01	1,930 75E−01
553	8,076 87E−04	9,473 98E−01	9,603 09E−01	4,33E−01	1,822 88E−01
554	7,325 68E−04	9,421 05E−01	9,657 85E−01	4,17E−01	1,719 30E−01
555	6,645 12E−04	9,358 29E−01	9,707 03E−01	4,02E−01	1,620 56E−01

Table 2 — Continued

λ (nm)	S-cone-opic $s_{sc}(\lambda)$	M-cone-opic $s_{mc}(\lambda)$	L-cone-opic $s_{lc}(\lambda)$	rhodopic $s_{rh}(\lambda)$	melanopic $s_{mel}(\lambda)$
556	6,028 87E−04	9,282 74E−01	9,747 56E−01	3,864E−01	1,526 01E−01
557	5,470 62E−04	9,196 67E−01	9,780 55E−01	3,715E−01	1,434 87E−01
558	4,964 61E−04	9,103 56E−01	9,808 19E−01	3,569E−01	1,347 48E−01
559	4,505 71E−04	9,006 77E−01	9,832 71E−01	3,427E−01	1,264 16E−01
560	4,089 31E−04	8,909 49E−01	9,856 36E−01	3,288E−01	1,185 26E−01
561	3,711 36E−04	8,813 86E−01	9,880 85E−01	3,151E−01	1,110 07E−01
562	3,368 38E−04	8,718 34E−01	9,905 60E−01	3,018E−01	1,037 93E−01
563	3,057 23E−04	8,620 59E−01	9,929 45E−01	2,888E−01	9,692 06E−02
564	2,775 04E−04	8,518 40E−01	9,951 24E−01	2,762E−01	9,042 59E−02
565	2,519 18E−04	8,409 69E−01	9,969 79E−01	2,639E−01	8,434 57E−02
566	2,287 25E−04	8,293 03E−01	9,984 11E−01	2,519E−01	7,861 98E−02
567	2,076 99E−04	8,169 11E−01	9,993 91E−01	2,403E−01	7,317 50E−02
568	1,886 38E−04	8,039 10E−01	9,999 12E−01	2,291E−01	6,802 88E−02
569	1,713 57E−04	7,904 13E−01	9,999 65E−01	2,182E−01	6,319 84E−02
570	1,556 88E−04	7,765 26E−01	9,995 43E−01	2,076E−01	5,870 13E−02
571	1,414 80E−04	7,623 11E−01	9,986 15E−01	1,974E−01	5,448 32E−02
572	1,285 96E−04	7,476 69E−01	9,970 51E−01	1,876E−01	5,048 89E−02
573	1,169 12E−04	7,324 76E−01	9,947 01E−01	1,782E−01	4,673 44E−02
574	1,063 16E−04	7,166 22E−01	9,914 16E−01	1,690E−01	4,323 57E−02
575	9,670 45E−05	7,000 13E−01	9,870 57E−01	1,602E−01	4,000 89E−02
576	8,798 58E−05	6,826 47E−01	9,815 99E−01	1,517E−01	3,701 02E−02
577	8,007 56E−05	6,648 17E−01	9,754 51E−01	1,436E−01	3,419 03E−02
578	7,289 79E−05	6,468 58E−01	9,691 20E−01	1,358E−01	3,155 62E−02
579	6,638 37E−05	6,290 72E−01	9,630 93E−01	1,284E−01	2,911 53E−02
580	6,047 05E−05	6,117 28E−01	9,578 41E−01	1,212E−01	2,687 47E−02
581	5,510 20E−05	5,949 98E−01	9,536 64E−01	1,143E−01	2,480 14E−02
582	5,022 69E−05	5,787 83E−01	9,502 36E−01	1,078E−01	2,285 97E−02
583	4,579 88E−05	5,629 35E−01	9,470 86E−01	1,015E−01	2,105 34E−02
584	4,177 59E−05	5,473 21E−01	9,437 52E−01	9,56E−02	1,938 64E−02
585	3,812 02E−05	5,318 25E−01	9,397 81E−01	8,99E−02	1,786 24E−02
586	3,479 74E−05	5,163 54E−01	9,348 26E−01	8,45E−02	1,645 78E−02
587	3,177 63E−05	5,008 70E−01	9,289 17E−01	7,93E−02	1,514 70E−02
588	2,902 88E−05	4,853 50E−01	9,221 77E−01	7,45E−02	1,393 14E−02
589	2,652 94E−05	4,697 77E−01	9,147 29E−01	6,99E−02	1,281 20E−02
590	2,425 49E−05	4,541 42E−01	9,066 93E−01	6,55E−02	1,179 01E−02
591	2,218 47E−05	4,384 54E−01	8,981 70E−01	6,13E−02	1,084 88E−02
592	2,029 96E−05	4,227 78E−01	8,891 88E−01	5,74E−02	9,971 12E−03
593	1,858 26E−05	4,071 88E−01	8,797 59E−01	5,37E−02	9,158 50E−03
594	1,701 82E−05	3,917 52E−01	8,698 94E−01	5,02E−02	8,412 42E−03
595	1,559 24E−05	3,765 27E−01	8,596 05E−01	4,69E−02	7,734 30E−03
596	1,429 24E−05	3,615 59E−01	8,489 12E−01	4,38E−02	7,112 55E−03
597	1,310 66E−05	3,468 56E−01	8,378 65E−01	4,09E−02	6,534 76E−03
598	1,202 48E−05	3,324 22E−01	8,265 22E−01	3,816E−02	6,001 10E−03
599	1,103 73E−05	3,182 61E−01	8,149 40E−01	3,558E−02	5,511 74E−03

Table 2 — Continued

λ (nm)	S-cone-opic $s_{sc}(\lambda)$	M-cone-opic $s_{mc}(\lambda)$	L-cone-opic $s_{lc}(\lambda)$	rhodopic $s_{rh}(\lambda)$	melanopic $s_{mel}(\lambda)$
600	1,013 56E−05	3,043 78E−01	8,031 73E−01	3,315E−02	5,066 86E−03
601	9,312 02E−06	2,907 84E−01	7,912 53E−01	3,087E−02	4,658 69E−03
602	8,559 41E−06	2,775 06E−01	7,791 18E−01	2,874E−02	4,279 46E−03
603	7,871 41E−06	2,645 75E−01	7,666 91E−01	2,674E−02	3,929 39E−03
604	7,242 21E−06	2,520 12E−01	7,539 00E−01	2,487E−02	3,608 72E−03
605	6,666 57E−06	2,398 37E−01	7,406 80E−01	2,312E−02	3,317 66E−03
606	6,139 70E−06	2,280 65E−01	7,269 95E−01	2,147E−02	3,051 09E−03
607	5,657 27E−06	2,167 03E−01	7,129 05E−01	1,994E−02	2,803 74E−03
608	5,215 35E−06	2,057 54E−01	6,984 91E−01	1,851E−02	2,575 60E−03
609	4,810 36E−06	1,952 21E−01	6,838 29E−01	1,718E−02	2,366 68E−03
610	4,439 06E−06	1,851 04E−01	6,689 91E−01	1,593E−02	2,176 98E−03
611	4,098 50E−06	1,753 98E−01	6,540 37E−01	1,477E−02	2,003 17E−03
612	3,785 99E−06	1,660 91E−01	6,389 79E−01	1,369E−02	1,841 90E−03
613	3,499 11E−06	1,571 69E−01	6,238 25E−01	1,269E−02	1,693 17E−03
614	3,235 63E−06	1,486 20E−01	6,085 79E−01	1,175E−02	1,556 92E−03
615	2,993 54E−06	1,404 31E−01	5,932 48E−01	1,088E−02	1,433 14E−03
616		1,325 91E−01	5,778 57E−01	1,007E−02	1,319 72E−03
617		1,250 92E−01	5,624 93E−01	9,32E−03	1,214 51E−03
618		1,179 28E−01	5,472 48E−01	8,62E−03	1,117 43E−03
619		1,110 91E−01	5,322 09E−01	7,97E−03	1,028 39E−03
620		1,045 73E−01	5,174 49E−01	7,37E−03	9,473 13E−04
621		9,836 63E−02	5,029 93E−01	6,82E−03	8,728 14E−04
622		9,246 85E−02	4,886 92E−01	6,30E−03	8,035 76E−04
623		8,687 59E−02	4,743 76E−01	5,82E−03	7,396 20E−04
624		8,158 34E−02	4,598 96E−01	5,38E−03	6,809 70E−04
625		7,658 41E−02	4,451 25E−01	4,97E−03	6,276 48E−04
626		7,186 83E−02	4,300 07E−01	4,59E−03	5,787 53E−04
627		6,741 86E−02	4,146 87E−01	4,24E−03	5,333 58E−04
628		6,321 76E−02	3,993 40E−01	3,913E−03	4,914 40E−04
629		5,924 92E−02	3,841 22E−01	3,613E−03	4,529 80E−04
630		5,549 90E−02	3,691 68E−01	3,335E−03	4,179 55E−04
631		5,195 50E−02	3,545 80E−01	3,079E−03	3,857 89E−04
632		4,861 03E−02	3,403 89E−01	2,842E−03	3,559 05E−04
633		4,545 91E−02	3,266 09E−01	2,623E−03	3,282 89E−04
634		4,249 45E−02	3,132 49E−01	2,421E−03	3,029 26E−04
635		3,970 97E−02	3,003 16E−01	2,235E−03	2,798 01E−04
636		3,709 52E−02	2,878 17E−01	2,062E−03	2,585 44E−04
637		3,463 47E−02	2,757 62E−01	1,903E−03	2,387 85E−04
638		3,231 25E−02	2,641 58E−01	1,757E−03	2,205 08E−04
639		3,011 51E−02	2,530 09E−01	1,621E−03	2,036 99E−04
640		2,803 14E−02	2,423 16E−01	1,497E−03	1,883 41E−04
641		2,605 64E−02	2,320 61E−01	1,382E−03	1,741 92E−04
642		2,420 11E−02	2,221 58E−01	1,276E−03	1,610 20E−04
643		2,247 60E−02	2,125 16E−01	1,178E−03	1,488 21E−04

Table 2 — Continued

λ (nm)	S-cone-opic $s_{sc}(\lambda)$	M-cone-opic $s_{mc}(\lambda)$	L-cone-opic $s_{lc}(\lambda)$	rhodopic $s_{rh}(\lambda)$	melanopic $s_{mel}(\lambda)$
644		2,088 70E−02	2,030 60E−01	1,088E−03	1,375 94E−04
645		1,943 66E−02	1,937 30E−01	1,005E−03	1,273 37E−04
646		1,812 00E−02	1,844 95E−01	9,28E−04	1,178 91E−04
647		1,691 49E−02	1,754 02E−01	8,57E−04	1,090 96E−04
648		1,579 91E−02	1,665 09E−01	7,92E−04	1,009 49E−04
649		1,475 43E−02	1,578 65E−01	7,32E−04	9,344 37E−05
650		1,376 60E−02	1,495 09E−01	6,77E−04	8,657 51E−05
651		1,282 46E−02	1,414 70E−01	6,26E−04	8,024 05E−05
652		1,193 04E−02	1,337 60E−01	5,79E−04	7,433 83E−05
653		1,108 50E−02	1,263 83E−01	5,36E−04	6,886 50E−05
654		1,028 92E−02	1,193 43E−01	4,96E−04	6,381 72E−05
655		9,543 15E−03	1,126 38E−01	4,59E−04	5,919 14E−05
656		8,846 09E−03	1,062 64E−01	4,25E−04	5,492 03E−05
657		8,196 00E−03	1,002 08E−01	3,935E−04	5,093 74E−05
658		7,590 59E−03	9,445 58E−02	3,645E−04	4,724 04E−05
659		7,027 54E−03	8,899 34E−02	3,377E−04	4,382 69E−05
660		6,504 55E−03	8,380 77E−02	3,129E−04	4,069 45E−05
661		6,019 52E−03	7,888 65E−02	2,901E−04	3,779 90E−05
662		5,570 93E−03	7,421 91E−02	2,689E−04	3,509 66E−05
663		5,157 28E−03	6,979 52E−02	2,493E−04	3,258 57E−05
664		4,776 87E−03	6,560 50E−02	2,313E−04	3,026 47E−05
665		4,427 94E−03	6,163 84E−02	2,146E−04	2,813 20E−05
666		4,108 32E−03	5,788 57E−02	1,991E−04	2,615 87E−05
667		3,814 70E−03	5,433 66E−02	1,848E−04	2,431 58E−05
668		3,543 92E−03	5,098 11E−02	1,716E−04	2,260 17E−05
669		3,293 29E−03	4,780 96E−02	1,593E−04	2,101 48E−05
670		3,060 50E−03	4,481 32E−02	1,480E−04	1,955 35E−05
671		2,843 69E−03	4,198 31E−02	1,375E−04	1,819 82E−05
672		2,641 75E−03	3,931 11E−02	1,277E−04	1,693 02E−05
673		2,453 74E−03	3,678 92E−02	1,187E−04	1,574 93E−05
674		2,278 75E−03	3,440 98E−02	1,104E−04	1,465 53E−05
675		2,115 96E−03	3,216 60E−02	1,026E−04	1,364 80E−05
676		1,964 56E−03	3,005 09E−02	9,54E−05	1,271 43E−05
677		1,823 78E−03	2,805 94E−02	8,88E−05	1,184 07E−05
678		1,692 87E−03	2,618 61E−02	8,26E−05	1,102 69E−05
679		1,571 15E−03	2,442 60E−02	7,69E−05	1,027 23E−05
680		1,457 98E−03	2,277 38E−02	7,15E−05	9,576 37E−06
681		1,352 74E−03	2,122 38E−02	6,66E−05	8,930 33E−06
682		1,254 76E−03	1,976 79E−02	6,20E−05	8,325 43E−06
683		1,163 40E−03	1,839 86E−02	5,78E−05	7,761 35E−06
684		1,078 12E−03	1,710 92E−02	5,38E−05	7,237 73E−06
685		9,984 24E−04	1,589 39E−02	5,01E−05	6,754 25E−06
686		9,239 62E−04	1,474 92E−02	4,67E−05	6,304 99E−06
687		8,547 13E−04	1,367 73E−02	4,36E−05	5,884 07E−06

Table 2 — Continued

λ (nm)	S-cone-opic $s_{sc}(\lambda)$	M-cone-opic $s_{mc}(\lambda)$	L-cone-opic $s_{lc}(\lambda)$	rhodopic $s_{rh}(\lambda)$	melanopic $s_{mel}(\lambda)$
688		7,906 52E−04	1,268 04E−02	4,06E−05	5,491 15E−06
689		7,316 84E−04	1,175 90E−02	3,789E−05	5,125 92E−06
690		6,776 53E−04	1,091 23E−02	3,533E−05	4,788 04E−06
691		6,282 97E−04	1,013 73E−02	3,295E−05	4,473 47E−06
692		5,831 08E−04	9,425 68E−03	3,075E−05	4,178 29E−06
693		5,415 84E−04	8,769 17E−03	2,870E−05	3,902 43E−06
694		5,032 94E−04	8,160 76E−03	2,679E−05	3,645 83E−06
695		4,678 70E−04	7,594 53E−03	2,501E−05	3,408 41E−06
696		4,350 07E−04	7,065 88E−03	2,336E−05	3,187 39E−06
697		4,044 90E−04	6,572 52E−03	2,182E−05	2,979 98E−06
698		3,761 38E−04	6,112 62E−03	2,038E−05	2,786 04E−06
699		3,497 84E−04	5,684 40E−03	1,905E−05	2,605 48E−06
700		3,252 78E−04	5,286 07E−03	1,780E−05	2,438 19E−06
701		3,024 77E−04	4,915 73E−03	1,664E−05	2,282 25E−06
702		2,812 37E−04	4,570 86E−03	1,556E−05	2,135 80E−06
703		2,614 27E−04	4,249 08E−03	1,454E−05	1,998 74E−06
704		2,429 30E−04	3,948 32E−03	1,360E−05	1,871 01E−06
705		2,256 41E−04	3,666 75E−03	1,273E−05	1,752 52E−06
706		2,094 78E−04	3,402 97E−03	1,191E−05	1,641 97E−06
707		1,944 00E−04	3,156 32E−03	1,114E−05	1,538 06E−06
708		1,803 70E−04	2,926 24E−03	1,043E−05	1,440 73E−06
709		1,673 47E−04	2,712 13E−03	9,76E−06	1,349 93E−06
710		1,552 86E−04	2,513 27E−03	9,14E−06	1,265 60E−06
711		1,441 35E−04	2,328 95E−03	8,56E−06	1,186 83E−06
712		1,338 30E−04	2,158 36E−03	8,02E−06	1,112 73E−06
713		1,243 09E−04	2,000 71E−03	7,51E−06	1,043 26E−06
714		1,155 13E−04	1,855 21E−03	7,04E−06	9,783 85E−07
715		1,073 88E−04	1,721 08E−03	6,60E−06	9,180 78E−07
716		9,988 00E−05	1,597 50E−03	6,18E−06	8,617 05E−07
717		9,293 20E−05	1,483 42E−03	5,80E−06	8,086 40E−07
718		8,649 07E−05	1,377 87E−03	5,44E−06	7,588 53E−07
719		8,050 90E−05	1,279 98E−03	5,10E−06	7,123 13E−07
720		7,494 53E−05	1,189 00E−03	4,78E−06	6,689 91E−07
721		6,976 52E−05	1,104 33E−03	4,49E−06	6,284 44E−07
722		6,494 70E−05	1,025 63E−03	4,21E−06	5,902 39E−07
723		6,047 18E−05	9,526 02E−04	3,951E−06	5,543 63E−07
724		5,632 07E−05	8,849 59E−04	3,709E−06	5,207 98E−07
725		5,247 48E−05	8,223 96E−04	3,482E−06	4,895 31E−07
726		4,891 42E−05	7,645 85E−04	3,270E−06	4,602 51E−07
727		4,561 37E−05	7,111 10E−04	3,070E−06	4,326 48E−07
728		4,254 90E−05	6,615 70E−04	2,884E−06	4,067 10E−07
729		3,969 89E−05	6,156 12E−04	2,710E−06	3,824 20E−07
730		3,704 43E−05	5,729 17E−04	2,546E−06	3,597 66E−07
731		3,456 88E−05	5,332 06E−04	2,393E−06	3,385 28E−07

Table 2 — Continued

λ (nm)	S-cone-opic $s_{sc}(\lambda)$	M-cone-opic $s_{mc}(\lambda)$	L-cone-opic $s_{lc}(\lambda)$	rhodopic $s_{rh}(\lambda)$	melanopic $s_{mel}(\lambda)$
732		3,225 88E−05	4,962 34E−04	2,250E−06	3,184 90E−07
733		3,010 26E−05	4,617 82E−04	2,115E−06	2,996 44E−07
734		2,808 93E−05	4,296 54E−04	1,989E−06	2,819 81E−07
735		2,620 88E−05	3,996 70E−04	1,870E−06	2,654 93E−07
736		2,445 29E−05	3,716 90E−04	1,759E−06	2,500 26E−07
737		2,281 77E−05	3,456 50E−04	1,655E−06	2,354 24E−07
738		2,129 95E−05	3,214 94E−04	1,557E−06	2,216 81E−07
739		1,989 41E−05	2,991 55E−04	1,466E−06	2,087 89E−07
740		1,859 65E−05	2,785 53E−04	1,379E−06	1,967 40E−07
741		1,740 03E−05	2,595 83E−04	1,299E−06	1,854 26E−07
742		1,629 31E−05	2,420 61E−04	1,223E−06	1,747 36E−07
743		1,526 32E−05	2,258 09E−04	1,151E−06	1,646 66E−07
744		1,430 05E−05	2,106 74E−04	1,084E−06	1,552 12E−07
745		1,339 65E−05	1,965 28E−04	1,022E−06	1,463 70E−07
746		1,254 49E−05	1,832 71E−04	9,62E−07	1,380 62E−07
747		1,174 41E−05	1,708 68E−04	9,07E−07	1,302 08E−07
748		1,099 29E−05	1,592 90E−04	8,55E−07	1,228 05E−07
749		1,029 00E−05	1,485 06E−04	8,06E−07	1,158 48E−07
750		9,633 97E−06	1,384 82E−04	7,60E−07	1,093 32E−07
751		9,022 63E−06	1,291 79E−04	7,16E−07	1,032 02E−07
752		8,453 01E−06	1,205 42E−04	6,75E−07	9,740 05E−08
753		7,922 07E−06	1,125 19E−04	6,37E−07	9,192 74E−08
754		7,427 00E−06	1,050 61E−04	6,01E−07	8,678 07E−08
755		6,965 22E−06	9,812 26E−05	5,67E−07	8,195 87E−08
756		6,534 22E−06	9,166 41E−05	5,35E−07	7,742 02E−08
757		6,131 29E−06	8,564 55E−05	5,05E−07	7,312 43E−08
758		5,753 91E−06	8,003 02E−05	4,77E−07	6,906 93E−08
759		5,399 84E−06	7,478 58E−05	4,50E−07	6,525 34E−08
760		5,067 11E−06	6,988 27E−05	4,25E−07	6,167 49E−08
761		4,754 13E−06	6,529 66E−05	4,01E−07	5,830 44E−08
762		4,460 19E−06	6,101 28E−05	3,790E−07	5,511 24E−08
763		4,184 66E−06	5,701 83E−05	3,580E−07	5,209 72E−08
764		3,926 90E−06	5,329 96E−05	3,382E−07	4,925 75E−08
765		3,686 17E−06	4,984 30E−05	3,196E−07	4,659 16E−08
766		3,461 57E−06	4,663 22E−05	3,021E−07	4,407 82E−08
767		3,251 55E−06	4,364 24E−05	2,855E−07	4,169 62E−08
768		3,054 64E−06	4,085 01E−05	2,699E−07	3,944 44E−08
769		2,869 51E−06	3,823 46E−05	2,552E−07	3,732 18E−08
770		2,695 04E−06	3,577 81E−05	2,413E−07	3,532 72E−08
771		2,530 40E−06	3,346 76E−05	2,282E−07	3,344 51E−08
772		2,375 50E−06	3,130 07E−05	2,159E−07	3,166 00E−08
773		2,230 33E−06	2,927 61E−05	2,042E−07	2,997 12E−08
774		2,094 78E−06	2,739 08E−05	1,932E−07	2,837 82E−08
775		1,968 64E−06	2,564 11E−05	1,829E−07	2,688 03E−08

Table 2 — Continued

λ (nm)	S−cone-opic $s_{sc}(\lambda)$	M-cone-opic $s_{mc}(\lambda)$	L-cone-opic $s_{lc}(\lambda)$	rhodopic $s_{rh}(\lambda)$	melanopic $s_{mel}(\lambda)$
776		1,851 52E−06	2,402 05E−05	1,731E−07	2,548 00E−08
777		1,742 48E−06	2,251 60E−05	1,638E−07	2,416 60E−08
778		1,640 60E−06	2,111 45E−05	1,551E−07	2,291 67E−08
779		1,545 07E−06	1,980 46E−05	1,468E−07	2,171 05E−08
780		1,455 18E−06	1,857 66E−05	1,390E−07	2,052 58E−08

NOTE 1 This table contains data from 380 nm to 780 nm. Cells have been left empty at present where no data are available for those wavelengths. The rhodopic action spectrum values are reproduced from ISO 23539/CIE S 010 without modifications. The S-cone opic action spectrum is provided for 390 nm to 615 nm, and the M- and L-cone-opic action spectra are provided for 390 nm to 780 nm, all reproduced from (CIE, 2006). By definition, the S-, M- and L-cone-opic action spectra take a maximum value of exactly 1 at 447,9 nm, 541,3 nm and 568,6 nm respectively. The melanopic action spectrum is reproduced from the underlying model in the Toolbox from (CIE, 2015), interpolated (cubic spline) from 5 nm to 1 nm resolution, and rounded to the nearest six significant figures for consistency with the cone fundamentals in (CIE, 2006).

NOTE 2 When calculating S-cone-opic quantities from spectral data in practice, only the wavelength range from 390 nm to 615 nm is to be considered (as the data outside this wavelength range are lacking at present). Similarly, when calculating M- and L-cone-opic quantities from spectral data in practice, only the wavelength range from 390 nm to 780 nm is to be considered (as the data below 390 nm are presently lacking for these photoreceptors).

NOTE 3 The value at 390 nm for the L-cone-opic action spectrum has been corrected from 4,07615E−04 (in (CIE, 2006)) to 4,07619E−04.

NOTE 4 These action spectra apply only to radiometric quantities. Wavelength-dependent conversion factors and renormalization would be needed to generate action spectra that apply to quantities defined in the spectral photon system.

Annex A
(informative)

A.1 Quantifying stimuli to photoreceptors by illuminants

Action spectra can be used to characterize the spectral qualities of illuminants according to their potential in eliciting biological stimulation and sensation. The $V(\lambda)$ function for photopic vision represents the photopic spectral luminous efficiency for humans and is used to characterize illuminants according to their ability to enable visual tasks. $V(\lambda)$ is mainly composed of M-cone-opic and L-cone-opic responses, albeit with an adjustment for the macular pigment. For IIL responses, it is unknown yet how the effect magnitude depends on the stimulation of different photoreceptors (for the significance of melanopsin, see A.4).

Table A.1 gives examples of common illuminants and light sources and their input to the different photoreceptor types. This could in future enable a more precise selection or design of illuminants to achieve a desired non-image-forming effect in an application.

Table A.2 gives examples of the melanopic irradiance and the melanopic equivalent daylight (D65) illuminance of various common illuminants and light sources at an illuminance of 100 lx.

A.2 α-opic equivalent daylight (D65) quantities

For any photometric quantity, the corresponding α-opic equivalent daylight (D65) quantity can be calculated by multiplying the photometric quantity by the α-opic daylight (D65) efficacy ratio, $\gamma_{\alpha,\mathrm{v}}^{\mathrm{D65}}$ (see Definition 3.10). The term "α-opic equivalent daylight (D65)" is used as a prefix to the name of the quantity, but the unit itself remains unchanged. This may be applied to photometric quantities like e.g. luminous flux (unit lm), luminous energy (unit lm·s), luminous exposure (unit lx·s), luminous exitance (unit $\mathrm{lm \cdot m^{-2}}$), luminous intensity (unit cd or $\mathrm{lm \cdot sr^{-1}}$), luminance (unit $\mathrm{cd \cdot m^{-2}}$), and others.

The following examples are given:

a) A white LED lamp, with a luminous flux of 800 lm and a melanopic daylight (D65) efficacy ratio of 0,428, has a melanopic equivalent daylight (D65) luminous flux of 342,4 lm.

b) A white LED flat panel light source, with a luminance of 1 500 $\mathrm{cd \cdot m^{-2}}$ and a melanopic daylight (D65) efficacy ratio of 0,8, has a melanopic equivalent daylight (D65) luminance of 1 200 $\mathrm{cd \cdot m^{-2}}$.

c) A single high-power green LED chip (521 nm), with a luminous flux of 90 lm in an emission angle of 80° (at 50 % intensity), a luminous intensity of 55 cd and a melanopic daylight (D65) efficacy ratio of 1,05, has a melanopic equivalent daylight (D65) luminous flux of 94,5 lm and a melanopic equivalent daylight (D65) luminous intensity of 57,75 cd.

Table A.1 —Various α-opic efficacies of luminous radiation (see Definition 3.4) as calculated for different common illuminants and light sources

Common illuminant or light source	S-cone-opic efficacy of luminous radiation $K_{\mathrm{sc,v}}$ (mW·lm⁻¹)	M-cone-opic efficacy of luminous radiation $K_{\mathrm{mc,v}}$ (mW·lm⁻¹)	L-cone-opic efficacy of luminous radiation $K_{\mathrm{lc,v}}$ (mW·lm⁻¹)	Rhodopic efficacy of luminous radiation $K_{\mathrm{rh,v}}$ (mW·lm⁻¹)	Melanopic efficacy of luminous radiation $K_{\mathrm{mel,v}}$ (mW·lm⁻¹)
Equi-energy spectrum	0,756	1,397	1,639	1,330	1,201
CIE standard illuminant A	0,254	1,174	1,657	0,831	0,657
Fluorescent 3 000 K (CIE illuminant FL12, interpolated to 1 nm)	0,293	1,163	1,636	0,736	0,534
Fluorescent 4 000 K (CIE illuminant FL11, interpolated to 1 nm)	0,483	1,267	1,615	0,938	0,745
CIE illuminant D55 (daylight 5 500 K)	0,686	1,411	1,629	1,338	1,199
CIE standard illuminant D65 (daylight 6 500 K)	0,817	1,456	1,629	1,450	1,326
CIE illuminant LED-B1	0,242	1,137	1,656	0,714	0,539
CIE illuminant LED-B2	0,296	1,174	1,647	0,782	0,607
CIE illuminant LED-B3	0,506	1,287	1,625	1,013	0,839
CIE illuminant LED-B4	0,662	1,334	1,604	1,087	0,916
CIE illuminant LED-B5	0,847	1,408	1,606	1,280	1,134
CIE illuminant LED-BH1	0,268	1,149	1,644	0,746	0,546
CIE illuminant LED-RGB1	0,199	1,199	1,660	0,976	0,766
CIE illuminant LED-V1	0,268	1,161	1,669	0,827	0,658
CIE illuminant LED-V2	0,489	1,323	1,644	1,152	1,000

NOTE The data given in this table apply only to the spectra as defined for common illuminants and light sources. Although the CIE illuminants defined for LEDs and fluorescent lamps are based on typical commercially available samples of products, it is important to note that they cannot be assumed to apply for all sources with a similar description. In particular there may be significant changes in 'typical' sources as technology develops as well as variations between different types and different manufacturers.

Table A.2 — Melanopic irradiance, melanopic equivalent daylight (D65) illuminance, melanopic efficacy of luminous radiation and melanopic daylight (D65) efficacy ratio, according to Definitions 3.6, 3.9, 3.4 and 3.10 respectively, as calculated for different common illuminants and light sources, for an illuminance, E_v, arbitrarily set to 100 lx

Common illuminant or light source	Illuminance E_v (lx)	Melanopic irradiance E_mel (mW·m⁻²)	Melanopic equivalent daylight (D65) illuminance $E_\mathrm{v,mel}^\mathrm{D65}$ (lx)	Melanopic efficacy of luminous radiation (of the light source) $K_\mathrm{mel,v}$ (mW·lm⁻¹)	Melanopic daylight (D65) efficacy ratio $\gamma_\mathrm{mel,v}^\mathrm{D65}$
Equi-energy spectrum	100	120,1	90,6	1,201	0,906
CIE standard illuminant A	100	65,7	49,6	0,657	0,496
Fluorescent 3 000 K (CIE illuminant FL12, interpolated to 1 nm)	100	53,4	40,4	0,534	0,404
Fluorescent 4 000 K (CIE illuminant FL11, interpolated to 1 nm)	100	74,5	56,2	0,745	0,562
CIE illuminant D55 (daylight 5 500 K)	100	119,9	90,4	1,199	0,904
CIE standard illuminant D65 (daylight 6 500 K)	100	132,6	100,0	1,326	1,000
CIE illuminant LED-B1	100	53,9	40,6	0,539	0,406
CIE illuminant LED-B2	100	60,7	45,8	0,607	0,458
CIE illuminant LED-B3	100	83,9	63,2	0,839	0,632
CIE illuminant LED-B4	100	91,6	69,0	0,916	0,690
CIE illuminant LED-B5	100	113,4	85,5	1,134	0,855
CIE illuminant LED-BH1	100	54,6	41,2	0,546	0,412
CIE illuminant LED-RGB1	100	76,6	57,8	0,766	0,578
CIE illuminant LED-V1	100	65,8	49,6	0,658	0,496
CIE illuminant LED-V2	100	100,0	75,4	1,000	0,754

NOTE The data given in this table apply only to the spectra as defined for common illuminants and light sources. Although the CIE illuminants defined for LEDs and fluorescent lamps are based on typical commercially available samples of products, it is important to note that they cannot be assumed to apply for all sources with a similar description. In particular there may be significant changes in 'typical' sources as technology develops as well as variations between different types and different manufacturers.

A.3 Equivalent illuminance and previous applications

As daylight is a naturally occurring stimulus, it is a relevant benchmark for general lighting applications. This standard uses standard daylight (standard illuminant D65) as the reference illuminant to provide the definitions of the α-opic equivalent daylight (D65) luminances and the α-opic equivalent daylight (D65) illuminances.

Instead of D65, other reference illuminants (like standard illuminant A or equi-energy illuminant E) can be used to define similar equivalent luminances and illuminances.

The α-opic equivalent equi-energy (E) illuminance was the first example of the "equivalent illuminance" concept to be introduced in the literature for IIL responses (Lucas et al., 2014), (CIE, 2015). It was defined as the illuminance of equi-energy (E) radiation required to provide equal α-opic irradiance as the test irradiance, for a given α. The quantities introduced by these publications were called α-opic equivalent illuminance, without explicit reference to the equi-energy reference radiation. Furthermore, although the units were given as "α-opic lux", in retrospect it should have been noted that the correct SI unit for these five quantities was lux (SI symbol lx), and that the "α-opic" in "α-opic lux" was only introduced as a short-hand approach to convey which of the five α-opic sensitivities was being used. This short-hand is not SI-compliant, and is now generally proscribed. The equivalent illuminance concept introduced in (Lucas et al., 2014) need not be restricted to the α-opic sensitivity curves or to using the equi-energy illuminant as a reference illuminant. Moreover, the "photometric equivalent" concept can be applied to quantities other than illuminance (unit lx or $\mathrm{lm \cdot m^{-2}}$), such as the luminous energy (unit $\mathrm{lm \cdot s}$), luminous intensity (unit cd or $\mathrm{lm \cdot sr^{-1}}$) and luminance (unit $\mathrm{cd \cdot m^{-2}}$ or $\mathrm{lm \cdot sr^{-1} \cdot m^{-2}}$), for example see Definition 3.8.

The underlying concept of equivalent illuminance (Lucas et al., 2014) has been preserved in this standard, but has been treated in a more rigorous and metrologically correct manner. Using the notation defined in this standard, it is possible to write a direct equation for the α-opic equivalent equi-energy (E) illuminance that Lucas et al. denoted as "α-opic equivalent illuminance":

$$E_{\mathrm{v},\alpha}^{\mathrm{E}} \equiv K_{\mathrm{N}} \int E_{\mathrm{e},\lambda}(\lambda)\, s_{\alpha}(\lambda)\, \mathrm{d}\lambda \tag{A.1}$$

where the constant K_{N} is given by

$$K_{\mathrm{N}} = K_{\mathrm{m}} \frac{\int E_{\mathrm{e},\lambda}^{\mathrm{E}}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda}{\int E_{\mathrm{e},\lambda}^{\mathrm{E}}(\lambda)\, s_{\alpha}(\lambda)\, \mathrm{d}\lambda} \tag{A.2}$$

By definition of the equi-energy illuminant (superscript E), the spectral irradiance, $E_{\mathrm{e},\lambda}^{\mathrm{E}}(\lambda)$, is independent of λ, i.e. it is a spectrally uniform function.

Using 1 nm summations over the wavelength range from 380 nm to 780 nm in place of the integrals in Equations (A.1) and (A.2), and renormalizing the action spectrum, $s_{\alpha}(\lambda)$, such that $\sum E_{\mathrm{e},\lambda}^{\mathrm{E}}(\lambda)\, s_{\alpha}(\lambda)\, \Delta\lambda = 1\ \mathrm{W \cdot m^{-2}}$, the normalization constant, K_{N}, is defined as $K_{\mathrm{N}} \approx 72\ 983\ \mathrm{lm \cdot W^{-1}}$, where K_{N} is independent of α; in other words K_{N} is the same for all five photoreceptors. If the sensitivity curves are normalized to have a maximum value of 1, as defined in this standard, K_{N} will depend on α.

From the date of publication of this standard:

- E_{α} should be taken to denote $E_{\mathrm{e},\alpha} = \int E_{\mathrm{e},\lambda}(\lambda)\, s_{\alpha}(\lambda)\, \mathrm{d}\lambda$ and be described as α-opic irradiance (see Definition 3.6).
- the subscript letters {sc, mc, lc, rh, mel} should be used to denote S-cone-opic, M-cone-opic, L-cone-opic, rhodopic and melanopic respectively; this is a change from the subscripts {sc,

mc, lc, r, z} used by Lucas et al. (2014) to denote cyanopic, chloropic, eryhtropic, rhodopic and melanopic respectively.

- E_{mel} is taken to denote $E_{\mathrm{e,mel}} = \int E_{\mathrm{e},\lambda}(\lambda)\, s_{\mathrm{mel}}(\lambda)\, \mathrm{d}\lambda$ and should be described as melanopic irradiance.

The concept ”melanopic illuminance”, M_{φ}, with units “melanopic lx”, first defined by Enezi et al. (2011), and the concept “melanopic equivalent illuminance”, E_z, with units “melanopic equivalent lx”, defined in (Lucas et al., 2014), are not supported under the SI system and should not be used. To convert M_{φ} and E_z into melanopic irradiance (E_{mel}), the following relationship can be used: $\left|M_{\varphi}\right| / 4\,557 \approx \left|E_{\mathrm{z}}\right| / 832{,}41 = \left|E^{\mathrm{E}}_{\mathrm{v,mel}}\right| / 832{,}41 \approx \left|E_{\mathrm{mel}}\right|$, where the magnitudes relate to these four quantities when expressed in “melanopic lux”, “equivalent melanopic lux”, lx and $\mathrm{W{\cdot}m^{-2}}$ respectively.

A.4 The melanopic action spectrum

The following steps have been adopted to derive the melanopic action spectrum as employed in this standard (see also (Lucas et al., 2014) and (CIE, 2015)):

1) The action spectrum of the human melanopsin protein can be described by an (opsin:vitamin A)-based photopigment template (Govardovskii et al., 2000) with a peak around 480 nm (Bailes and Lucas, 2013, and the review by Lucas et al., 2014). This yields an action spectrum that is consistent with the spectral sensitivities recorded for melanopsin-driven responses in several other mammalian species (including primates) (Berson et al., 2002; Dacey et al., 2005; Lucas et al., 2001). Moreover, the action spectrum for a persistent pupil constriction in humans following a bright light flash (the so-called post-illumination pupil response), which has been attributed to melanopsin in primates, is consistent with the template-based melanopsin action spectrum (Gamlin et al., 2007).
2) The physical self-screening adjustment to account for the optical pigment density of melanopsin in ipRGCs is considered negligible.
3) A pre-receptoral filtering adjustment is applied to account for the optical path to the peripheral retina. This adjustment is based on the pre-receptoral filtering for a reference observer of age 32 years as adopted in (Lucas et al., 2014) and detailed in (CIE, 2015). Moreover, the influence of macular pigment on the melanopsin action spectrum is considered negligible (i.e. there is no allowance for macular pigment in $s_{\mathrm{mel}}(\lambda)$).
4) The melanopsin action spectrum as obtained in Step 3 is adjusted from the spectral photon system to the spectral (energy-based) radiometric system.
5) The melanopsin action spectrum as obtained in Step 4 is normalized to have a maximum value of 1. This contrasts (Lucas et al., 2014), where the melanopsin sensitivity function (of Step 4) is normalized so that an equi-energy source (E) with a given illuminance would produce the same spectrally weighted quantities for all five photoreceptors.

An additional potential consideration in defining the melanopic action spectrum is the possibility that melanopsin may be a so-called bi (or tri) stable photopigment (Emanuel and Do, 2015). Bistable pigments form a thermally stable state upon light exposure that is itself light sensitive and can switch off signalling upon photon absorption. In such pigments, responses to one wavelength of light can be strongly impacted by exposure to a second wavelength to which the photoproduct is very sensitive. In theory then, estimates of melanopsin spectral sensitivity based upon action spectra derived from exposure to narrow-band or monochromatic sources are not necessarily predictive for responses to polychromatic stimuli. In practice, explicit tests of this possibility have indicated that it is not a significant consideration in vivo (Gamlin et al., 2007; Enezi et al., 2011; Bailes and Lucas, 2013; Brown et al., 2013).

A.5 Pre-receptoral filtering and spectral age correction

The human lens becomes less transparent and yellows with age (Pokorny et al., 1987). The action spectra provided in (Lucas et al., 2014) are based on pre-receptoral filtering for a reference observer of age 32 years, chosen as to be comparable to the age of the CIE 1931 standard colorimetric observer, see also (CIE, 2015). For observers of a different age a spectral correction may be applied. The correction can be based on the age-dependent transmittance function (CIE, 2012). It is emphasized that these corrections apply to averages, as there is considerable individual variation (Mellerio, 1987) and ageing of the lens accelerates in tropical environments (Luthra et al., 1994). People who have undergone cataract surgery can have an increased transmittance in the short wavelength range and may need a dedicated spectral correction for their pre-receptoral filtering.

In September 2012, the CIE published an erratum to (CIE, 2012), which gives the approximate function for the absolute transmission of the human eye for wavelengths from 300 nm to 700 nm for large field sizes. However, this function is considered to remain broadly valid up to 780 nm. Therefore, the function has been applied up to 780 nm to calculate the age-related data in Figure A.1 and Table A.3. Note that this approach is slightly different to the one used in Lucas et al. (2014) and to the one used in (CIE, 2006).

Since the absolute transmittance for a 32-year-old observer is already included in the melanopic action spectrum, $s_{\mathrm{mel}}(\lambda)$, it follows that when determining the correction function for age, this correction, too, has to be related to a 32-year-old reference observer. This is done by defining the correction function to be 1 at all wavelengths for a = 32 years and calculating the spectral correction function $c(a,\lambda)$ for wavelength λ and age a from the ratio of the transmittance function $\tau(a,\lambda)$ to the transmittance function $\tau(32,\lambda)$ for age 32 years, these transmittance functions being as defined by CIE (2012)

$$c(a,\lambda)=\frac{\tau(a,\lambda)}{\tau(32,\lambda)} \tag{A.3}$$

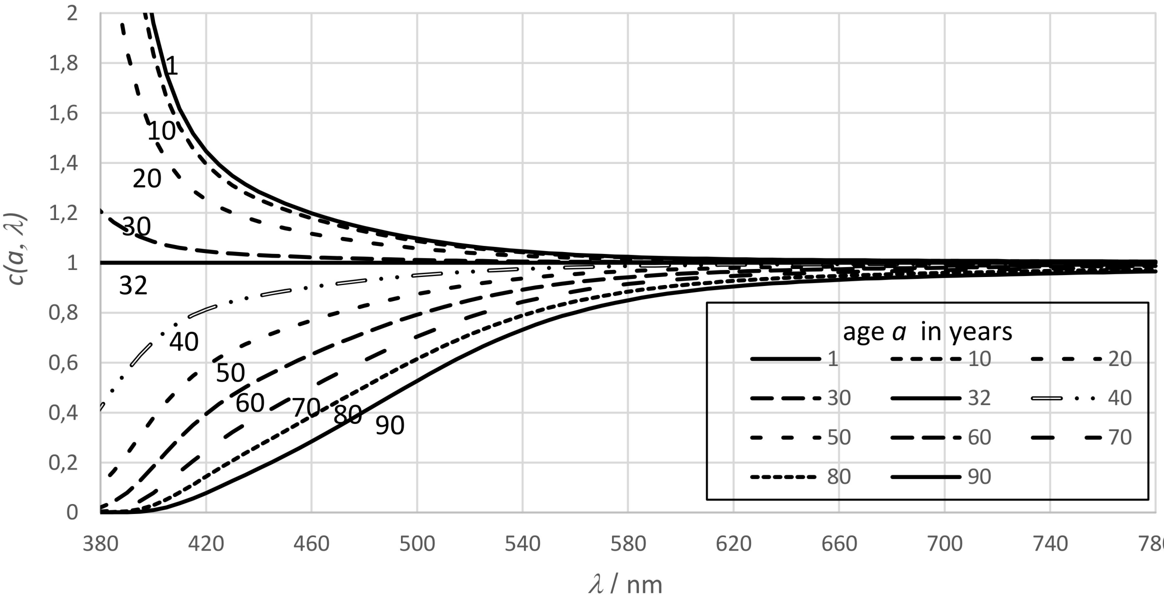

Figure A.1 — Spectral correction function $c(a, \lambda)$ for different ages

Although the spectral age correction is not intended for use in colorimetric contexts, it can be applied to the light input to the ipRGCs. The sensitivity functions for rods and cones inherently include pre-receptoral filtering in the data. When a spectral age correction is applied for the melanopic action spectrum, the same age correction should be applied to the other α-opic photoreceptors, for consistency.

Any α-opic quantity, as well as any α-opic equivalent daylight (D65) quantity can be converted to an age-corrected α-opic quantity for a given age a. As an example, the age correction of the melanopic equivalent daylight (D65) illuminance, $E_{\mathrm{v,mel}}^{\mathrm{D65}}$ (as given in Definition 3.9), is determined using the following equation:

$$E_{\mathrm{v,mel}}^{\mathrm{D65}}(a) = E_{\mathrm{v,mel}}^{\mathrm{D65}} \cdot k_{\mathrm{mel},\tau}(a) \tag{A.4}$$

where

$$k_{\mathrm{mel},\tau}(a) = \frac{\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} \Phi_{\mathrm{e},\lambda}(\lambda)\, c(a,\lambda)\, s_{\mathrm{mel}}(\lambda)\,\mathrm{d}\lambda}{\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} \Phi_{\mathrm{e},\lambda}(\lambda)\, s_{\mathrm{mel}}(\lambda)\,\mathrm{d}\lambda} \tag{A.5}$$

Note that, in order to calculate the "age-related transmittance ratio of melanopic efficacy", $k_{\mathrm{mel},\tau}(a)$, the spectral radiant flux, $\Phi_{\mathrm{e},\lambda}(\lambda)$, in Equation (A.5) can also be replaced by the spectral radiance, $L_{\mathrm{e},\lambda}(\lambda)$, or by the spectral irradiance, $E_{\mathrm{e},\lambda}(\lambda)$.

Examples for melanopic assessment of various illuminants and light sources are given in Table A.3.

Table A.3 — Age-related correction factors for melanopic quantities of several common illuminants and light sources

Common illuminant or light source	$k_{\mathrm{mel},\tau}$ **(25 years)**	$k_{\mathrm{mel},\tau}$ **(32 years)**	$k_{\mathrm{mel},\tau}$ **(50 years)**	$k_{\mathrm{mel},\tau}$ **(75 years)**	$k_{\mathrm{mel},\tau}$ **(90 years)**
Equi-energy spectrum	1,052	1,000	0,835	0,589	0,459
CIE standard illuminant A	1,042	1,000	0,863	0,646	0,523
Fluorescent 3 000 K (CIE illuminant FL12, interpolated to 1 nm)	1,045	1,000	0,857	0,641	0,524
Fluorescent 4 000 K (CIE illuminant FL11, interpolated to 1 nm)	1,050	1,000	0,842	0,608	0,484
CIE illuminant D55 (daylight 5 500 K)	1,050	1,000	0,840	0,598	0,468
CIE standard illuminant D65 (daylight, 6 500 K)	1,052	1,000	0,835	0,589	0,457
CIE illuminant LED-B1	1,043	1,000	0,861	0,643	0,521
CIE illuminant LED-B2	1,044	1,000	0,857	0,633	0,510
CIE illuminant LED-B3	1,048	1,000	0,845	0,609	0,482
CIE illuminant LED-B4	1,052	1,000	0,834	0,588	0,459
CIE illuminant LED-B5	1,054	1,000	0,829	0,575	0,442
CIE illuminant LED-BH1	1,042	1,000	0,864	0,653	0,536
CIE illuminant LED-RGB1	1,036	1,000	0,879	0,679	0,560
CIE illuminant LED-V1	1,044	1,000	0,861	0,645	0,523
CIE illuminant LED-V2	1,048	1,000	0,848	0,616	0,488

NOTE The data given in this table apply only to the spectra as defined for common illuminants and light sources. Although the CIE illuminants defined for LEDs and fluorescent lamps are based on typical commercially available samples of products, it is important to note that they cannot be assumed to apply for all sources with a similar description. In particular there may be significant changes in 'typical' sources as technology develops as well as variations between different types and different manufacturers.

A.6 Understanding the impact of field of view

There has been a tradition of measuring vertical illuminance or vertical irradiance at the corneal plane in many studies. This gives a measure of cosine-weighted radiance averaged over a full 2π steradian field of view. In most actual viewing situations, the spectrum and magnitude of radiance varies with angle. The relevant FOV is determined by the eyelids and gaze angle. Physical baffles (radiance hoods) can be placed over a cosine detector to measure spatially averaged radiance or luminance entering the eye.

The human eye has a vertical FOV ranging upward to about 50° to 55° above the line-of-sight, indoors and under low illumination (Sliney and Wolbarsht, 1980). However, in extremely bright outdoor sunlight conditions (e.g. a desert environment) the upper lid lowers involuntarily (potentially signaled by the ipRGCs) and the upper limit for the vertical FOV is restricted to as little as ~15° above the line-of-sight (Deaver et al., 1996; Sliney, 2002). The lateral field of view is limited by the nose for each eye such that the lateral field of view is about 144° to 147° with temporal values just under 90° (~87°) and the maximal nasal detection at ~60°, thus when one wishes to account for the lateral FOV of both eyes, 180° is reasonable for most measurements. Table A.4 shows typical FOV values, for indoor and outdoor conditions, suitable for a measurement (instrument) that mimics the viewing condition for assessments of a spatially averaged radiance or luminance, i.e. for determining the retinal irradiance or illuminance.

Table A.4 — Typical field of view as determined by the eyelids

Environmental illumination	Vertical extent	Horizontal extent (left-right)
Indoor	50° above 0° to 70 ° below 0°	180° (with both eyes)
Outdoor	20° above 0° to 70° below 0°	180° (with both eyes)

NOTE 1 Greater detail regarding the effective field of view is given below.

NOTE 2 In unusually bright indoor light conditions (like a light therapy room) a smaller, more outdoor like, vertical FOV may be appropriate.

NOTE 3 For IIL responses the FOV is reasonably represented by the FOV with both eyes open. However, for practical reasons a horizontal extent of 180° is considered to be appropriate, although in Note 1 to entry of the definition of field of vision in the ILV (CIE S 017) a value of 190° is given.

When applying the FOV limits of Table A.4, care should be taken to allow for FOV variations over time. This may be particularly important in outdoor and daylight environments. Retinal photoreceptor signalling is thought to be spatially- and time-averaged, with the head and eye moving over the averaging time-frame. The FOV limits given in Table A.4 are centred around an instantaneous direction of gaze. Over the averaging time-frame, the direction of gaze can be variable, and although for some tasks it is typically slightly downwards (Deaver et al., 1996; MIL-STD-1472F, 1999) it may include brief, but possibly significant contributions from above and below the stated FOV limits. It is also important to appreciate that there is considerable variation among individuals viewing the same luminance field. For all these reasons, the values in Table A.4 are only suggestive of typical values, particularly for outdoor environments (Deaver et al., 1996).

Spatial variability of ipRGCs

The total cone density is greatest in the fovea and decreases with off-axis angle. The rods and S-cones are largely absent in the fovea. The rods initially increase in density as the off-axis angle increases. However, the exact spatial distribution of ipRGCs is still under investigation, as are the spatial determinants of IIL responses and the potential cone and rod inputs. For example, it remains unclear how these factors of receptive field size and ipRGC distribution manifest in responses such as the pupillary light reflex. Using blue monochromatic sources, Joyce et al. (2016) studied the pupillary response to light for central and peripheral stimulation. Moreover, various studies have explored differences in acute melatonin suppression depending on the spatial parameters of the stimulus, with heterogeneous results, see (Adler et al., 1992; Lasko et al., 1999; Visser et al., 1999; Glickman et al., 2003).

Retinal Illuminance

When viewing a limited FOV light source, or when mapping the retinal irradiance of a spatially varying light source, instead of employing Equations (1) to (3), the retinal illuminance is sometimes evaluated in terms of conventional retinal illuminance, which can be expressed in the non-SI unit troland (Td). The conventional retinal illuminance in Td equals the source luminance (in $cd \cdot m^{-2}$) multiplied by the pupillary area in mm^2. However, eye movements over time can blur the retinal illuminance of the image. Therefore, the measure of radiance over the whole field of view could be more informative than a single irradiance measure.

Vertical illuminance

In cases where spatial variations in light distribution are absent (e.g. for Ganzfeld exposures), or can be ignored (e.g. for large area light sources), vertical illuminance measurement at the eye position can provide a useful estimation of retinal illuminance. However, vertical illuminance only indicates an average over a hemisphere. As such, it can include contributions from direct light sources (like luminaires or the sun) even when these direct light sources are overhead and outside the FOV limits as given in Table A.4. To exclude these contributions from outside the FOV limits (Table A.4), a hood can be placed over the detector of the (vertical) illuminance measurement.

Illuminance and irradiance

A full-field spatial measurement of light includes overhead light that normally does not reach the retina due to blocking by the upper eye-lid. This raises the question which FOV is a sensible choice for a study. The answer depends upon the objective of the measurement. Vertically measured radiation (irradiance, spectral irradiance, illuminance) only is clearly adequate under controlled laboratory conditions where the individual is viewing a uniform Ganzfeld sphere. In some controlled laboratory experiments, investigators employed an annular FOV, with the central (foveal) zone obscured. Otherwise, for example when subjects are performing tasks under overhead luminaires, a 180° horizontal FOV is not unreasonable, but the total vertical FOV should be much less; for example, up to 90° total vertical angle of acceptance outdoors (i.e. −70° to +20°) and up to 120° indoors (i.e. −70° to +50°). All these values are only suggested, as the individual variability in vertical FOV is significant, and, in both instances, often aimed downward along the gaze angle where visual tasks are performed. It should be emphasized that many surfaces in nature and in built environments have lower reflectance in the blue end of the spectrum – thus altering the spectral distribution from overhead luminaires or sunlight. Moreover, the region of the retina being exposed to radiation may be important: an equal illuminance from either an upper hemisphere or a lower hemisphere does not produce equivalent areas of retinal exposure. This is due to the different vertical FOV coverages, see Table A.4.

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