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Quantifying irradiance for eye-mediated non-image forming effects of light in humans

Bewertung von Strahlung für nichtvisuelle Wirkungen von Licht bei Aufnahme über die Augen

Quantification de l'éclairement énergétique pour les effets non formateurs d'image de la lumière transmise par le biais des yeux chez l'homme

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17.180.20	Barve in merjenje svetlobe	Colours and measurement of light

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EUROPEAN COMMITTEE FOR STANDARDIZATION
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European foreword

This document (CEN/TR 16791:2017) has been prepared by Technical Committee CEN/TC 169 “Light and lighting”, the secretariat of which is held by DIN.

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Introduction

There is strong scientific evidence that light is not only essential for vision but also elicits important biological, non-image-forming effects that are highly relevant for human performance and well-being.

The non-image-forming effects can be either eye or skin mediated (e.g. vitamin D production, skin cancer or solar dermatitis). This document focuses on the eye-mediated non-image-forming effects. Depending on time of light exposure, spectral power distribution, duration of exposure, and individual parameters like circadian phase, light history, and others, light can cause suppression of the nocturnal release of melatonin, increase heart rate as well as alertness and affect thermoregulation [17], or the electroencephalogram spectrum. Light is the main synchroniser of the human biological clock. It can shift the phase of the circadian system and determines the timing of sleep/wake cycle. In a proportion of patients, light exposure can alleviate seasonal and non-seasonal depression and improve quality of life [1]. Upon light exposure, fast responses in the range of seconds were seen in the pupillary reflex or in brain activity.

The current lighting practice and the tendency for energy saving, e.g. European Regulations 244/2009 and 859/2009 as well as 245/2009 and 347/2010 tend to reduce indoor illumination levels. This can create lighting conditions that are sub-optimal for human well-being, health and functioning.

The above mentioned biological effects of light are elicited by stimulation of ocular photoreceptors. The receptors for vision, the rods and cones, are relatively well understood and characterized by standards such as CIE S 017. Although melanopsin containing retinal ganglion cells (intrinsically photosensitive Retinal Ganglion Cells, ipRGCs) play an important role in the non-image-forming effects of light, this photoreceptor is not yet included in existing lighting standards and recommendations. Therefore, a description of optical radiation solely according to the photopic action spectrum is not sufficient. The actual biological effect to ocular exposure to light will depend on the relative response of all photoreceptors and there is good evidence for synergistic responses between the receptors. For a deeper understanding of how a stimulation of the photoreceptors leads to a desirable or undesirable biological effect, light will be characterized in a way to quantify the input to each of the five known photoreceptors.

It is also important to recognize the importance of darkness, and the daily pattern of light and dark, particularly around and during periods of sleep. Additionally, certain changes to the balance of the spectrum of light at different times of day might be helpful in promoting circadian rhythms [18], but further evidence would be needed to support this as a general principle. Analysing the involvement of different photoreceptors would be crucial to understand how such outcomes with impact on human health are provoked.

The biological non-visual effects of light have a direct impact on human performance and well-being with large implications for architecture, indoor design, and lighting as well as for social- and work-schedules. The integration of these effects in lighting applications and designs requires new metrics to quantify light.

This report contains input of experts that, at the time of writing, also have contributed to the Draft International Standard in preparation by CIE JTC 9 "CIE system for metrology of ipRGC influenced light response". This Technical Report is entirely informative in nature and, unlike CIE JTC 9, does not address field of view aspects. Consequently, insights, terminology, tables (on spectral sensitivity and age correction) and symbols used in this report may be outdated after publication of the new CIE standard.

1 Scope

This Technical Report proposes metrics that can be used to evaluate and compare lighting conditions with respect to their potential to achieve non-image-forming, eye-mediated effects of light in human beings. This document applies to visible optic radiation in the wavelength range from 380 nm to 780 nm.

This Technical Report does not give information for particular lighting applications.

This Technical Report does not address health safety issues such as resulting from flicker, photobiological safety or the effects of non-visible optical radiation (ultraviolet and infrared radiation).

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.

EN 12665, *Light and lighting - Basic terms and criteria for specifying lighting requirements*

CIE S 017/E:2011, ILV: International Lighting Vocabulary

3 Terms and definitions

For the purposes of this document, the terms and definitions given in CIE S 017/E:2011, EN 12665 and the following apply.

NOTE The differences for definitions of spectrally-weighted quantities that follow the SI convention are given where applicable.

3.1
α-opic
relating to the characteristics in non-visual photometry of the specified human photoreceptor and its opsin-based photopigment, denoted by α

Note 1 to entry: The symbol α represents one of the five photopigments. α can take one of five values, set out in Table 1. See 3.1.1 to 3.1.5.

Note 2 to entry: Based on [13].

3.1.1
S-photopic
relating to S-photopsin, the human S-cone photopigment (α = “sp”)

Note 1 to entry: S-photopsin is sometimes denoted as cyanopsin. In this report the term S-photopic is used to differ from other publications that are using slightly different sensitivity functions and denoting this sensitivity by the word cyanopic.

Note 2 to entry: The maximum of S-cone sensitivity is in the blue spectral region at 445 nm. S denotes maximum sensitivity at short wavelengths.

Note 3 to entry: The function for S-photopic sensitivity is based on the 10° cone fundamentals in CIE 170–1:2006.

3.1.2
M-photopic
relating to M-photopsin, the human M-cone photopigment (α = "mp")

Note 1 to entry: M-photopsin is sometimes denoted as chloropsin. In this report the term M-photopic is used to differ from other publications that are using slightly different sensitivity functions and denoting this sensitivity by the word chloropic.

Note 2 to entry: The maximum of M-cone sensitivity is in the green spectral region at 540 nm. M denotes maximum sensitivity at medium wavelengths.

Note 3 to entry: The function for M-photopic sensitivity is based on the 10° cone fundamentals in CIE 170–1:2006.

3.1.3
L-photopic
relating to L-photopsin, the human L-cone photopigment (α = "lp")

Note 1 to entry: L-photopsin is sometimes denoted as erythropsin. In this report the term L-photopic is used to differ from other publications that are using slightly different sensitivity functions and denoting this sensitivity by the word erythropic.

Note 2 to entry: The maximum of L-cone sensitivity is in the yellow-red spectral region at 570 nm. L denotes maximum sensitivity at long wavelengths.

Note 3 to entry: The function for L-photopic sensitivity is based on the 10° cone fundamentals in CIE 170–1:2006.

3.1.4
scotopic

relating to rhodopsin, the human rod photopigment (α = "rod")

Note 1 to entry: Scotopic is sometimes denoted as rhodopic. Please note that in [13] the spectral sensitivity for rods is denoted as "rhodopic", but the values given there are not equivalent to CIE definitions for scotopic vision. This is the reason for use of "scotopic" in this document.

Note 2 to entry: The sensitivity function used in this technical report as scotopic is identical to V'(λ), the sensitivity function of the rods as defined in CIE S010:2005 (ISO 23539).

3.1.5
melanopic
relating to melanopsin, the photopigment contained in human ipRGC (α = "mel")

Note 1 to entry: The term usually indicates the photoreception of the ipRGCs that is driven by the photopigment melanopsin. The term "melanopic effects" can be used to denote non-visual effects that are mediated by the intrinsic photosensitivity of melanopsin containing ipRGCs. Even though melanopsin containing retinal ganglion cells are present in many different species, the data published here is only valid for humans mainly because of the inherent ocular transmittance data.

Note 2 to entry: The data used in this report for melanopic sensitivity is based on [13], but the sensitivity function has been normalized to a maximum that is equal to 1 at 490 nm.

Note 3 to entry: The function for melanopic sensitivity is including the pre-receptoral filtering by the human ocular system for a reference observer at an age of 32 years.

3.2
α-opic spectral efficiency (of monochromatic radiation of wavelength λ)
$s_\alpha(\lambda)$
spectral sensitivity of one of the five human α-opic photopigments to irradiance incident at the eye's outer surface of a standard observer, normalized to the maximum of 1

Note 1 to entry: The unit of the α-opic spectral efficiency is 1.

Note 2 to entry: The spectral efficiency function $s_\alpha(\lambda)$ is representing the relative spectral effectiveness of optical radiation to stimulate the α-opic photopigment at wavelength λ in relation to its maximum effectiveness at wavelength $\lambda_{\alpha,\max}$ which is defined as 1 for each of the five α-opic photopigments. Equivalent terms for spectral efficiency function are "action spectrum" or "spectral weighting function".

Note 3 to entry: The effectiveness of polychromatic radiation to stimulate the α-opic photopigment is assessed by spectrally weighting the spectral power distribution of the polychromatic radiation by the spectral efficiency function as described in 3.3.

3.3
α-opic radiant quantity
spectral radiant quantity weighted with the α-opic spectral efficiency defined by the formula

$$X_{e,\alpha} = \int X_{e,\lambda}(\lambda)\, s_\alpha(\lambda)\, d\lambda \quad (1)$$

where

$X_{e,\lambda}(\lambda)$ is the spectral radiant quantity;

$s_\alpha(\lambda)$ is the α-opic spectral efficiency (of monochromatic radiation of wavelength λ) as defined in 4.2.2, Table 2.

Note 1 to entry: In general $X_{e,\lambda}(\lambda)$ is a spectral radiometric quantity. E.g. when $X_{e,\lambda}(\lambda)$ is the spectral radiant flux ($\Phi_{e,\lambda}(\lambda)$), $X_{e,\alpha}$ represents the α-opic radiant flux which may be denoted by $\Phi_{e,\alpha}$. In this case the unit for $\Phi_{e,\alpha}$ would be W.

Note 2 to entry: In a second example $X_{e,\lambda}(\lambda)$ could be the spectral radiance. In this case $X_{e,\alpha}$ represents the α-opic radiance which may be denoted by $L_{e,\alpha}$ with units $W \cdot sr^{-1}$.

Note 3 to entry: In this document all integrals are referring to a lower wavelength of 380 nm and to an upper wavelength of 780 nm, corresponding to the definition range of Table 2.

3.4
α-opic efficacy of luminous radiation (of a light source)
$K_{\alpha,\mathrm{v}}$
quotient of the α-opic radiant quantity of a light source (with known spectral composition) to the corresponding photometric quantity

$$K_{\alpha,v} = \frac{\int X_{\mathrm{e},\lambda}(\lambda) \cdot \mathrm{s}_{\alpha}(\lambda) \cdot \mathrm{d}\lambda}{K_{\mathrm{m}} \cdot \int X_{\mathrm{e},\lambda}(\lambda) \cdot V(\lambda) \cdot \mathrm{d}\lambda} \tag{2}$$

Note 1 to entry: The unit of the α-opic efficacy of luminous radiation (of a light source) is $\mathrm{W \cdot lm^{-1}}$.

Note 2 to entry: $K_{\alpha,\mathrm{v}}$ can be expressed as ratio of the α-opic radiant flux ($\Phi_{\mathrm{e},\alpha}$) to the luminous flux (Φ_{v})

$$K_{\alpha,v} = \frac{\Phi_{\mathrm{e},\alpha}}{\Phi_{V}} \tag{3}$$

When the fluxes are expressed per unit area, Formula (3) equals the quotient of the α-opic irradiance to the photopic illuminance

Note 3 to entry: For practical reasons it is recommended to modify the unit to W/klm or to mW/lm.

Note 4 to entry: For the special case of a light source with characteristics of standard illuminant D65, Formula (3) defines the α-opic efficacy of daylight $K_{\alpha,v}^{\mathrm{D65}}$.

$$K_{\alpha,v}^{\mathrm{D65}} = \frac{\Phi_{\mathrm{e},\alpha}^{\mathrm{D65}}}{\Phi_{\mathrm{V}}^{\mathrm{D65}}} \tag{4}$$

3.5
α-opic irradiance
$E_{\mathrm{e},\alpha}$
α-opic radiant flux per unit area

$$E_{\mathrm{e},\alpha} = \frac{\Phi_{\mathrm{e},\alpha}}{F} \tag{5}$$

where

F is the area which is uniformly irradiated by $\Phi_{\mathrm{e},\alpha}$

Note 1 to entry: The unit of the α-opic irradiance is $\mathrm{W \cdot m^{-2}}$.

Note 2 to entry: α-opic irradiance is usually measured in the outward-facing plane normal to the optical axis at the outer surface of the eye.

3.6
α-opic equivalent daylight (D65) illuminance
$E_{v,\alpha}^{D65}$

illuminance $E_{v,\alpha}^{D65}$ of a light source with spectral characteristics of standard illuminant D65 that provides an equal α-opic irradiance $E_{e,\alpha}$ as the test source

$$E_{v,\alpha}^{D65} = \frac{E_{e,\alpha}}{K_{\alpha,v}^{D65}} \quad (6)$$

Note 1 to entry: The unit of the α-opic equivalent daylight (D65) illuminance is lx.

Note 2 to entry: Examples for the melanopic equivalent daylight (D65) illuminance of different light sources at the same photopic illuminance are given in Table A.2.

3.7
α-opic daylight (D65) efficacy ratio (with luminous radiation)
$\gamma_{\alpha,v}^{D65}$

ratio of the α-opic efficacy of luminous radiation $K_{\alpha,v}$ of the test light condition (Formula (3)) to the α-opic efficacy of luminous radiation of daylight $K_{\alpha,v}^{D65}$ (Formula (4))

$$\gamma_{\alpha,v}^{D65} = \frac{K_{\alpha,v}}{K_{\alpha,v}^{D65}} \quad (7)$$

Note 1 to entry: The unit of the α-opic daylight (D65) efficacy ratio (with luminous radiation) is 1.

Note 2 to entry: $\gamma_{\alpha,v}^{D65}$ can also be expressed as the ratio of the melanopic equivalent daylight illuminance to the photopic illuminance of the test light condition. It can also be expressed in percent, where 1 equals 100 %. In this case the value of the α-opic daylight (D65) efficacy ratio $\gamma_{\alpha,v}^{D65}$ in percent is equal to the value of the α-opic equivalent daylight illuminance $E_{\alpha,v}^{D65}$ of a test light condition S that delivers a photopic illuminance of 100 lx.

Note 3 to entry: For the case that α denotes melanopsin, $\gamma_{mel,v}^{D65}$ can alternatively be denoted as the melanopic daylight (D65) efficacy ratio (MDER) of the test light condition. In this case MDER should be given as a number instead of a percentage. Some MDER values for different light sources are given in Table A.2. By multiplying the photopic illuminance of a test light condition measured in lx with MDER, the value of the melanopic equivalent daylight illuminance in lx is obtained.

3.8
circadian rhythm
biological rhythm with a period of approximately 24 h

Note 1 to entry: Biological rhythms are endogenous and affect psychology, physiology and behaviour.

Note 2 to entry: The sleep/wake cycle is an example of an endogenous circadian rhythm.

[SOURCE: CIE S 017/E: 2011 17-176; modified: notes to entry added]