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TECHNICAL NOTE

Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013

CIE TN 003:2015

CIE Technical Notes (TN) are short technical papers summarizing information of fundamental importance to CIE Members and other stakeholders, which either have been prepared by a TC, in which case they will usually form only a part of the outputs from that TC, or through the auspices of a Reportership established for the purpose in response to a need identified by a Division or Divisions.

This Technical Note has been prepared by CIE Reportership 6-42 of Division 6 “Photobiology and Photochemistry”, to report on the proceedings and consensus of the invited experts of *The 1st International Workshop on Circadian and Neurophysiological Photometry*, 2013 (the Workshop), which acts on the basis of a consensus of the participants, who are also the advisers to this report. The review article of the Workshop (Lucas, 2014) takes precedence for the interpretation of the scientific consensus also set out here. Every attempt has been made to ensure this report correctly describes the consensus. The opinions expressed in Clauses 4 and 6 of this report do not form a part of the Workshop consensus and are not necessarily the opinions of the participants.

Any mention of organizations or products does not imply endorsement by CIE. Whilst every care has been taken in the compilation of any lists, up to the time of going to press these may not be comprehensive.

This report summarizes the discussions at, and outcomes from, the Workshop. It is not intended to represent the view of the CIE in relation to circadian and neurophysiological photometry. Indeed some recommendations from the Workshop are in direct conflict with CIE recommendations and with the guidance on use of SI units published by the CIPM (International Committee on Weights and Measures); these cases are highlighted in the report and the CIE recommendations are outlined.

The following member of DR 6-42 “Report on the 1st International Workshop for Action Spectra of Non Image Forming Photobiological Effects of Light” took part in the preparation of this Technical Note:

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All fourteen of the above took part in *The 1st International Workshop on Circadian and Neurophysiological Photometry*, 2013. Selected roles within the workshop and related standard setting bodies are listed.

S.N. Peirson and L.L.A. Price have developed the toolbox for calculation and conversions between units for light measurements on behalf of the workshop, with notable assistance from R.J. Lucas, T.M. Brown, G.C. Brainard and his colleagues B. Warfield and J.P. Hanifin at Thomas Jefferson University, and K. Baczynska of Public Health England.

CONTENTS

Summary

This Technical Note deals with the role of the eye in processing light information and the measurement of the eye's light exposure, with particular emphasis on the physiological or photobiological effects whose distinction from visual perception has become widely recognized since the discovery of melanopsin in human retinal ganglion cells. The Technical Note summarizes the proceedings and consensus of *The 1st International Workshop on Circadian and Neurophysiological Photometry* ("IWCNP 2013", the "Workshop") and aims to provide an interpretation for governments, the lighting community and professionals working in public health, and to highlight the importance of scientific advances and the growing evidence base in this area.

On 28 February 2013 a report was formally requested by Division 6 of the CIE, to summarize the views of an independent scientific workshop of international experts in the fields of circadian and neurophysiological photoreception, primarily composed of non-lighting specialists, for whose work the measurement of light has become an important issue. The role of rapporteur was offered to and accepted by Luke L.A. Price, GB.

The reportership was originally charged with producing a report to the CIE, which the CIE would issue as a free downloadable electronic publication. The CIE felt that an independent workshop would provide a step towards future measurement standards related to the non-visual effects of light on health. However, as some of the IWCNP recommendations might be mistaken for CIE recommendations or even standards, and as in some places these do not comply with the SI system, which the CIE supports, the scope of the reportership was modified.

The intention of these changes are that this Technical Note shall replace the need for the report originally requested, and include CIE comments related to its own measurement recommendations. This publication is available as a freely downloadable electronic document, together with an SI-compliant version of the Workshop's toolbox (downloadable at http://files.cie.co.at/784_TN003_Toolbox.xls), which it is hoped will support researchers in expressing their measurements as SI quantities and in SI units.

It is important to appreciate that the difference between the Workshop and CIE recommendations relates solely to the description of quantities and units, and not their underlying nature. Every care has been taken to ensure the reader can easily distinguish between the IWCNP and CIE systems. The CIE is prepared to support the Workshop consensus provided compliant SI units are adopted.

1 Executive summary of the Workshop and its consensus

This report gives a brief account of the proceedings of *The 1st International Workshop on Circadian and Neurophysiological Photometry* ("IWCNP 2013", the "Workshop") and its consensus statements. It concludes with an interpretation and summary which do not form part of the consensus of the Workshop participants.

Measurements of timing and the biological factors of primary interest to circadian, neuroendocrine and neurobehavioural-related photobiology researchers are typically accurate and chosen to describe the quantities of direct interest. By contrast, light stimuli have often been less well described by researchers.

One of the goals of research into non-visual responses to light is to establish what qualities of light are important. Unsurprisingly then, published illuminance (unit: lux) and correlated colour temperature (CCT) values, symbol[1] T_{cp} (unit: kelvin), have proved insufficient for replicating experimental conditions. Illuminance levels are even reported in lux for experiments on animals; despite being a base unit of the International System for Units (SI), the candela uniquely depends on human biology and visual perception. Similarly papers often quote the manufacturer and model of artificial illuminants used as a substitute for describing the spectral qualities of the light incident at the eye.

Notable attempts to review and combine the new action spectra for melatonin suppression in humans began to be published and discussed in 2002. These highlighted the possibility of a new standardized measurement quantity for light to replace the photometric quantity of luminous flux when describing exposures for non-visual responses and illustrated some of the challenges.

R.J. Lucas and G.C. Brainard first discussed fostering a scientific consensus on the problem of the measurement of light at the 41st annual meeting of the Society for Neuroscience, held in November 2011, in Washington DC. Following discussions with other interested parties, an independent scientific workshop with a CIE Division 6 Reportership was identified as the best vehicle to encourage improvements in light measurement for circadian and neurophysiological photometry.

The Workshop was held in Didsbury, Manchester, United Kingdom, on 10-12 January 2013. It concluded that convincing evidence for a single action spectrum explaining all circadian and neurophysiological effects under all conditions in humans or animals does not exist. In fact there is unlikely to be one widely applicable action spectrum. The shortcomings of the existing evidence highlight the need for further research, including improved light measurements, and to revisit prior research where possible to add relevant unpublished details about light conditions.

The IWCNP consensus statements and recommendations have been published in a recent article (Lucas, 2014). They aim to recognize and review important research that has been completed and to promote greater detail and consistency in the measurement of light in future research into non-visual responses. In brief these are:

- A novel photopigment, melanopsin, has recently been discovered in a sub-class of retinal ganglion cells, and there is a good understanding of its action spectrum.
- Neither this photopigment nor any classical photopigment, present in rod and cone cells, is sufficient alone to fully explain individual systemic responses to light.
- Calibrated spectral measurements should be recorded in published research to enable experimental conditions to be accurately replicated and lighting conditions between studies to be compared, by evaluating the stimulus intensities for all five photopigments.
- As scientific work in the field is ongoing to establish the relationships between light stimuli and non-visual effects, the Workshop should reconvene in five years, or earlier, when it will be appropriate to update the current information.

[1] The symbol T_c stands for Colour Temperature, a property of blackbodies, and T_{cp} for Correlated Colour Temperature, a property of the radiation of any light source with a chromaticity close to the Planckian locus, by analogy to T_c. As T_c is often used for T_{cp}, the context is important when comparing values for T_c.

In addition to the consensus statements, non-visual action spectra for all five photopigments were agreed.

2 The 1st International Workshop on Circadian and Neurophysiological Photometry

Notable attempts to review and combine the new action spectra data for melatonin suppression (Brainard, 2001; Thapan, 2001) began to be published and discussed in 2002 (Rea, 2002; Schulmeister, 2002; Gall, 2004; Rea, 2005).

These highlighted the possibility of a new standardized measurement quantity to replace the photometric quantity of luminous flux (unit: lumen) when describing exposures for circadian and neurophysiological responses, although J.B. O'Hagan recognized there would be significant barriers to producing a universally accepted standard. For general acceptance, any standard would need to follow from a consensus within the scientific community. It was also hoped that later research might better explain differences in results from other experimental methods, such as that of Hankins and Lucas (Hankins, 2002).

R.J. Lucas and G.C. Brainard first discussed fostering a scientific consensus on the problem of the measurement of light at the 41st annual meeting of the Society for Neuroscience, held in November 2011, in Washington DC. At subsequent discussions in December 2011 in Eindhoven at the European Committee for Standardization Technical Committee 169 on Light and Lighting, Working Group 13 on the Non-visual effects of light on human beings (CEN/TC 169/WG 13), an independent scientific workshop with a CIE Division 6 reportership was identified as the best vehicle to encourage improvements in light measurement for circadian and neurophysiological photometry.

The Workshop was organized and chaired by R.J. Lucas and G.C. Brainard and hosted at Didsbury Park Hotel on 10-12 January 2013, with administrative assistance from the University of Manchester. The Workshop funding was provided by Zentralverband Elektrotechnik und Elektronikindustrie e.V. (ZVEI, Frankfurt, Germany), a consortium of German electrical and electronic manufacturers. ZVEI's foresight and generosity in placing no pre-conditions on the Workshop outputs ensured the Workshop was free to form an independent scientific view.

The stated purpose of the Workshop was "*to address the question of how melanopsin photoreceptors impact methods of measuring light by bringing key contributors together to compose a review article, which summarizes current areas of consensus and uncertainty and, to the extent that this is possible, provides advice for measuring light*."

The Workshop intends to reconvene along similar lines within five years to update the position that has currently been reached.

2.1 Workshop protocol

Eligibility for invitations to the Workshop applied to:

- Participants, still working in the field, representing groups that had published relevant action spectra or directly addressed the problem of light measurement posed by the discovery of melanopsin, or
- Participants chairing relevant standards committees.

This was subject to acceptance of the following:

- Workshop rules on confidentiality,
- Joint accountability regarding Workshop consensus, and
- Provision of a declaration of interests, relevant current industry relationships and intellectual property rights.

Confidentiality rules were required to create an environment where the participants would feel free to hold open scientific discussions and share findings from relevant unpublished research.

As well as the interest and support shown by CIE and CEN/TC 169/WG 13, the IWCNP recommendations are being considered by other international standards bodies, including the International Organization for Standardization (ISO) and the Illuminating Engineering Society of North America (IESNA).

The Workshop participants were aware that they would be invited to act as advisers to this Technical Note to CIE, following the publication of the review article, and that the two chairs and J.B. O'Hagan would debrief CEN/TC 169/WG 13.

2.2 Presentation of scientific evidence

The two chairs welcomed the participants and set out the purpose of the Workshop. The Workshop participants all gave brief personal introductions and indicated to the others any interests they had to declare. J.B. O'Hagan then gave a presentation to familiarize the participants with the interests and structures of regulators and other interested parties.

Several of the experts were then invited to make 30-minute presentations. These presentations included the latest published and unpublished evidence from their research to ensure subsequent discussions would be fully informed.

There were seven presentations, concluding at lunch on the second day, as follows:

- R.J. Lucas – Wavelength sensitivity of human melanopsin
- D.M. Berson – Circuitry and sensitivity for rod and cone influences on ipRGCs. What's new?
- M.G. Figueiro – Measuring Circadian Light
- S.N. Peirson – A simple application to determine the light available for NIF [non image forming] photoreception
- S.W. Lockley – "Circadian" photoreception: Multiple neuro-endocrine and neuro-behavioural responses
- D.J. Skene – Can non-visual responses to polychromatic light be predicted by melanopsin?
- G.C. Brainard – Quantifying light: the implications of three human melatonin suppression fluence response curves relative to three different polychromatic light spectra

The evidence was discussed openly at intervals throughout the presentations. Towards the end of these sessions the consensus position was emerging.

2.3 Breakout groups

The next order of business was to create content and consensus statements for the review article. Three smaller discussion groups were formed. Each group was instructed to create a draft outline for the review article, identify the key "known and unknown questions in the field", and consider "best practice for light measurement".

The following three breakout groups had been pre-chosen by the chairs:

- Group A – D.M. Berson, P.D. Gamlin, M.G. Figueiro and S.W. Lockley
- Group B – G.C. Brainard, T.M. Brown, H.M. Cooper and I. Provencio
- Group C – C.A. Czeisler, R.J. Lucas, S.N. Peirson and D.J. Skene

During this period, J.B. O'Hagan and L.L.A. Price moved between the groups to observe and were available to provide technical input relating to light measurements and standards, for example. Following these discussions, each group prepared electronic documents to capture their proposals.

2.4 Synthesis and agreed actions

Within three hours, the breakout groups rejoined and compared outlines, which were fairly similar. The main ideas were combined into a lead document by the end of the second day.

On the third and final day, pairs of experts were instructed to draft more detailed sections for the review article, which were then discussed a little time later. There were also significant periods of discussion concerning preferences for standard nomenclature and units.

The experts agreed that light is potent in eliciting a wide array of circadian, neuroendocrine and neurobehavioural response in humans. These responses originate in the eye but are relatively separate from other aspects of vision. For instance, they are unrelated to particular spatial patterns of light exposure, and they are found in some blind persons. Consequently, these types of responses to light have sometimes been referred to as ‘non-visual’ or ‘non image forming’. Currently, there is no consensus on a single term for the broad range of biological, behavioural and health effects of light.

The units for the five photopigment-based weighted irradiance quantities were also discussed in some detail; the Workshop proposed that each should be given a “lux” unit normalized to have equal sensitivity to an equi-energy reference source (Standard Illuminant E) as the familiar photopic lux unit, but with its own specific spectral sensitivity.

S.N. Peirson proposed modifying an existing spreadsheet to become a “toolbox” for calculating values according to these units from spectral irradiance distributions (SIDs). More details are given below in Clause 5.

Towards the evening on the last day, L.L.A. Price set out the likely similarities and differences between the review article and this report. The meeting concluded with a summing up and a planning review. The participants were given take-home actions and a proposed schedule for completing the review article.

The IWCNP review article “Measuring and using light in the melanopsin age” (Lucas, 2014), the toolbox and user guide are available freely on the journal’s website, and CIE have made this Technical Note available freely on theirs. The CIE have also made a revised version of the toolbox incorporating SI units available, for the reasons set out immediately below (downloadable at http://files.cie.co.at/784_TN003_Toolbox.xls).

The use of new non-SI units and normalized spectral sensitivity functions, as proposed by the Workshop and set out in Annex B, is in direct conflict with the guidelines produced by the CIPM (International Committee on Weights and Measures) regarding the SI (the International System of Units) and is therefore not recommended by CIE. CIE recommends that all measurement quantities and their associated units are expressed in accordance with the SI; the use of non-SI units is strongly deprecated. Further details, including the CIE recommended approach for photobiological quantities and units, are given in Clause 4.

3 Consensus statements of the Workshop

Light causes circadian, hormonal and other behavioural responses, from shifting sleep timing, jet-lag and melatonin suppression to pupil constriction, light adaptation and physiological activation (Dijk, 2009). These wide ranging effects all depend on a new photoreceptor system found in the eye (Berson, 2002; Hattar, 2002) and this system was only recently identified following the discovery of melanopsin (Provencio, 1998), a light-sensitive photopigment which is also found in many other animals (Koyanagi, 2005).

Illuminance, measured in lux, has historically been used as the measure of light by researchers studying responses in both humans and animals. With the discovery of the importance of melanopsin and its human sensitivity in vivo (Gamlin, 2007), it is now known that using illuminance is inappropriate due to differences in spectral sensitivity. Unlike other units from the International System of Units (SI), the definitions of illuminance and the associated unit, lux, are based on human visual responses. Visual responses are mediated by a different photoreceptive system that sits alongside the non-visual system, but lacks melanopsin and captures instantaneous spatially-resolved information (images).

The consensus statements of the Workshop identify important areas where, at this moment in time, there is either agreement or uncertainty about the nature of this 'new' photoreceptor system and the wide range of responses it evokes. Advice is given to researchers, lighting professionals and regulators about the implications of current knowledge and the rate at which it is progressing.

Together, the human rods and cones contain four photopigments. Each has a different spectral sensitivity to light with broad wavelength ranges that overlap each other considerably, and ultimately determine the visibility of radiation. When plotted on a frequency scale, the shape of the spectral sensitivity is highly preserved between the photopigments, and all four sensitivities can be described with a single spectral template if the wavelength of maximum sensitivity to monochromatic radiation at the retina is known (Govardovskii, 2000).

The S-cone photopigment is most sensitive at shorter wavelengths, followed by the rod photopigment rhodopsin, the M-cone and finally the L-cone at increasing wavelengths. Melanopsin's maximum sensitivity lies between the S-cone opsin and rhodopsin at around 480 nm. The maximum sensitivity wavelength is slightly higher after allowing for the pre-receptor spectral filtering of light reaching the retina, bringing it closer to scotopic sensitivity (Enezi, 2011).

As all five photopigments are found in the new photoreceptor system, the stimulus for all five should be included in a completely general model. To use the model, light has to be measured in such a way that there is enough information to determine each of the five stimuli separately. The recommendation for research relating to circadian and neurophysiological effects is that spectral measurements, in the form of SIDs, are carefully collected and recorded. These can then be converted into the five components according the proposed new quantities and using the toolbox provided. (Note that a revised version of the toolbox accompanies this Technical Note, which allows the user to select SI compliant units and avoid the use of non-SI units, as recommended by CIE.)

The Workshop's aim is to establish a common reporting practice in the scientific literature that supports future meta-analyses of light studies. This approach should lead to a better understanding of physiological responses to light, and, in time, allow a firm basis for the production and measurement of light for interior and exterior environments.

The Workshop recognizes others have already made important contributions towards scientific standards for the measurement of light in relation to non-visual responses, and wish to emphasize in particular two significant reports which have come before:

- CIE 158:2009. Ocular Lighting Effects on Human Physiology and Behaviour
- IES TM-18-08. Light and Human Health: An Overview of the Impact of Light on Visual, Circadian, Neuroendocrine and Neurobehavioral Responses

3.1 Retinal organization and melanopsin

The photoreceptor cells in the retinas of vertebrates can be divided into three broad classes:

- Rods, responsible for scotopic vision,
- Cones, which mediate vision in the photopic range, and
- ipRGCs (intrinsically photosensitive retinal ganglion cells) that "encode irradiance".

These photoreceptors are sensitive in the wavelengths of visible radiation, i.e. light. The ipRGCs are rendered photosensitive through the expression of melanopsin, an opsin-based photopigment that is most sensitive to light at around 480 nm (Hankins, 2002; Dacey, 2005; Bailes, 2013).

The same peak wavelength for melanopsin responses is observed in different vertebrate species (Koyanagi, 2005; Panda, 2005; Qiu, 2005; Torii, 2007). This level of consistency of the peak wavelength is not seen in the 'classical' photopigments in rods and cones, although there is certainly consistency within species and, to a lesser extent, between similar species.

Melanopsin is thought to be bistable and may therefore have a more complex spectral sensitivity profile than the one-way responses of the rod and cone pigments, as is discussed later. Whether the response of melanopsin in humans depends on both a forward and a reverse action spectrum, in a *biologically-relevant* manner, remains to be determined.

ipRGCs in vertebrates share strong similarities to the primary photoreceptors found in invertebrates, including the molecular components of the phototransduction pathways. Melanopsin itself resembles rhabdomeric photopigments of invertebrates and the photopigment itself at the amino acid level (Provencio, 1998; Borges, 2012).

Retinal ganglion cells (RGCs), including ipRGCs, occupy a different cell layer to the rods and cones. Light passes through this layer to reach the rods and cones, except in the fovea. Each RGC, again including the intrinsically photosensitive RGCs, receives information from a number of rods and cones, indirectly, by way of synaptic contacts with the cell's branch-like protrusions known as dendrites (Berson, 2002; Hattar, 2002).

An ipRGC's dendrites stretch across a wide retinal area. As well as receiving information from other cells, the melanopsin in the dendrites is sensitive to light directly. Whichever route it takes, light causes the extended ipRGC membrane to depolarize by an amount related to its intensity. This controls the signals, in the form of successive action potentials that travel to the specialized areas of the brain, thereby "encoding irradiance" (Berson, 2002; Dacey, 2005). The frequency of the signals is related to the level and duration of the irradiance.

Depending upon conditions, cell activation (depolarization and the generation of signals) may persist long after lights off, as discussed later. Light-induced depolarization is not found in the rods and cones and post-stimulus persistence is significantly shorter in the rods and not found in the cones. The built-in photosensitivity of ipRGCs explains physiological and behavioural responses to light found in animals without functional rods and cones.

Rods and cones both pass information derived from incident light to ipRGCs. This results in responses from ipRGCs due to both rod and cone behaviour and the intrinsic photochemistry due to melanopsin. This explains how non-visual pathways continue to operate in genetically engineered animals without the melanopsin gene, but with intact ipRGCs (Panda, 2002; Panda, 2003; Ruby 2002; Lucas, 2003; Hattar, 2003).

At least five distinct types of ipRGCs have been described (namely M1, M2, M3, M4 and M5) (Ecker, 2010). They have different dendrite arrangements (morphology), inputs from rods and cones, melanopsin concentrations, photosensitivity, target cells and functions, all of which have not been fully characterized.

It is not clear whether or not different types of ipRGCs will be found to have different overall spectral and temporal responses. The spectral sensitivity function of any one type is likely to react to changing light conditions, because isolated rods, cones and ipRGCs react at different rates with different saturation points under sustained exposure to light.

Adding to this complexity is the range of destinations for signals from ipRGCs. The targeted subcortical regions of the brain include the suprachiasmatic nuclei (SCN) and hypothalamus. In mice it has been shown (Baver, 2008) that ~80 % of the innovating ipRGCs belong to the M1 sub-class, and 20 % to the M2 sub-class. By contrast the olivary pretectal nucleus (OPN) receives comparable inputs from both sub-classes (45 % : 55 %).

A general consensus is emerging that the circadian and neurophysiological response functions controlled by these target areas in the inner brain have different reactions to light, depending on both the spectrum and variations in irradiance over time.

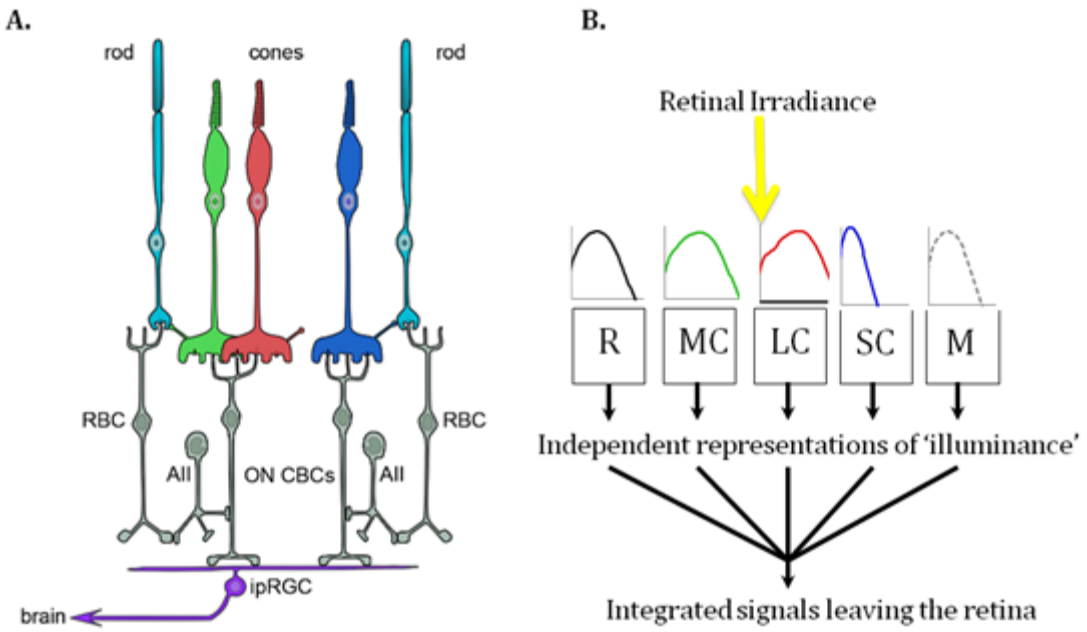


Figure 1 – All retinal photoreceptor classes are upstream of circadian, neuroendocrine and neurobehavioral responses to light
Reproduced with permission (Lucas, 2014)

Figure 1 shows two overviews that emphasize different details (cellular and spectral) of the five types of photoreceptor responsible for transduction of light in the retinal portion of the non-visual system and the routes the information subsequently takes up to the point it leaves the retina via the ipRGCs.

The left part of the figure (A.) shows a schematic of the relevant retinal circuitry in humans. Non-visual responses originate in the retina and are mediated by ipRGCs. Due to the expression of melanopsin, ipRGCs can also respond to light directly. ipRGCs are connected to the outer retinal rod and cones via the conventional retinal circuitry. The details are incompletely understood and may vary between different sub-types of ipRGCs. The circuitry includes connections via ON cone bipolar cells (on CBCs) to cone photoreceptors and connections via amacrine cells (AII) and rod bipolar cells (RBC) to rod photoreceptors. Hence the firing pattern of human ipRGCs can be influenced by melanopsin photoreception and signals from rods and three distinct cone classes (shown in red, green and blue).

The right part of the figure (B.) shows a simplified presentation: each photoreceptive mechanism absorbs light according to its own spectral sensitivity (shown as plots of log sensitivity against wavelength: R for rhodopsin; M for melanopsin; SC for S-cone opsin; MC for M-cone opsin; and LC for L-cone opsin) to generate a distinct measure of irradiance. The rod and cone input signals are then combined by the retinal wiring, and ultimately within the ipRGC itself with melanopsin phototransduction, to produce an integrated signal that is sent exclusively to non image forming centres in the brain. As each of the five independent representations of irradiance are produced by a photopigment with its own spectral sensitivity profile, their relative significance for the integrated output defines the wavelength dependence of this signal, and hence of downstream responses.

3.2 Photoreception dimensions: Five broadband sensitivity functions

Reporting the SID at the outer surface of the eye is recommended for measurements relating to systemic effects of light. The standard five spectrally-weighted values can be calculated from the SID data. These values simplify the description of the light conditions by selecting the most relevant components for human non-visual photoreception, and discarding any unnecessary information. In other words, the α-opic spectral efficiency functions, $N_\alpha(\lambda)$, set out in Table 1 form a set of spectral basis functions for standard human photoreception.

Table 1 – The photoreceptors of the human retina, their designation and formulae for α-opic equivalent illuminance, reproduced and modified with permission (Lucas, 2014), following the non-SI compliant approach from the Workshop (see Annex B), the use of which is strongly deprecated by CIE

Photoreceptor	Photopigment (label, α)	α-opic spectral efficiency, $N_\alpha(\lambda)$	Quantity (α-opic equivalent illuminance)	Quantity symbol (E_α)	Unit (α-opic equivalent lux)	Unit symbol
s-cone	photopsin (sc)	cyanolabe	cyanopic equivalent illuminance	E_{sc}	cyanopic equivalent lux	sc-lx
m-cone	photopsin (mc)	chlorolabe	chloropic equivalent illuminance	E_{mc}	chloropic equivalent lux	mc-lx
l-cone	photopsin (lc)	erythrolabe	erythropic equivalent illuminance	E_{lc}	erythropic equivalent lux	lc-lx
ipRGC	melanopsin (z)	melanopic	melanopic equivalent illuminance	E_z	melanopic equivalent lux	z-lx
rod	rhodopsin (r)	rhodopic	rhodopic equivalent illuminance	E_r	rhodopic equivalent lux	r-lx

Each α-opic illuminance is found by convolving the spectral irradiance, $E_{e,\lambda}(\lambda)$ (W·m^{-2}), for each wavelength, with the α-opic spectral efficiency function, $N_\alpha(\lambda)$, and multiplying by the non-visual spectral efficacy constant, K_N (α-lm·W^{-1}):

$$E_\alpha = K_N \int E_{e,\lambda}(\lambda) N_\alpha(\lambda) \mathrm{d}\lambda. \quad (1)$$

The values of $N_\alpha(\lambda)$ in equation (1) are given in Table A.1 (see Annex A).

The value for the non-visual spectral efficacy constant, K_N ≈ 73 000 α-lm·W^{-1}, is found from the equivalence condition in definition B.2 (see Annex B), which can be expressed as follows:

$$K_N \int \Phi_{e,\lambda}(\lambda) N_\alpha(\lambda) \mathrm{d}\lambda \,/\, \alpha\text{-lm} = K_m \int \Phi_{e,\lambda}(\lambda) V(\lambda) \mathrm{d}\lambda \,/\, \mathrm{lm} \quad (2)$$

for a uniform spectral flux $\Phi_{e,\lambda}(\lambda)$, i.e. an equi-energy spectrum.

The numerical value of K_N can be calculated as the product of the numerical value of the maximum value of the luminous efficacy of radiation, K_m (683,002), and the sum of the values of $V(\lambda)$ in the wavelength range of λ=360 nm to λ=830 nm (106,856 917 101 172) (published in CIE, 1983, p. 22), which agrees to 73 000 to within 0,025 %.

NOTE V in $V(\lambda)$ and E_V stands for visual, N in $N_\alpha(\lambda)$ and K_N for non-visual.

Table 2 (see Clause 4) sets out the SI-compliant approach strongly recommended by the CIE. As the proposed quantities and units proposed by the Workshop, set out in Table 1, are non-SI compliant, the CIE does not recommend their use. Although the IWCNP units produce results with similar magnitudes to photopic lux, there is no loss of information in using SI units. Either approach provides important and unambiguous information about the stimulus at the outer surface of the eye.

The spectral distributions of $N_\alpha(\lambda)$depend on a pre-receptoral transmittance function, $\tau(\lambda)$, for the ocular media for the standard human observer. Tabulated values at 5-nm intervals for $N_\alpha(\lambda)$ and $\tau(\lambda)$ are set out in Annex A. Five similar weighting functions or action spectra, $s_\alpha(\lambda)$,

are used when following the CIE recommendations. To comply with the SI system the functions are normalized to 1 at the peak. Values for $s_\alpha(\lambda)$ can be calculated as $N_\alpha(\lambda)$ / $N_\alpha(\lambda_{max})$, where λ_{max} is the wavelength of peak sensitivity.

The term “melanopic lux” has been previously introduced (Enezi, 2011). Because the Workshop selected a different form of normalization, a conversion factor is required to convert between the melanopic lux described by Enezi and the melanopic equivalent lux proposed by the Workshop, so that one ‘new’ melanopic equivalent lux ≈ 5,48 ‘old’ melanopic lux. For various reasons, there are also minor spectral differences between the standard observer transmittance function $\tau(\lambda)$ used by the Workshop and the transmittance function used to define “melanopic lux” (in Enezi, 2011), but for white light sources these differences are usually insignificant and the conversion factor remains accurate. For narrowband or monochromatic radiation lower conversion factors (i.e. lower than 5,48) apply at short wavelengths, and higher factors apply at long wavelengths. For an equi-energy spectrum it is possible to calculate the exact conversion factor as 4 557/$(K_N \cdot N_z(\lambda_{max}))$.

The five α-opic equivalent quantities are based on a typical 32-year-old observer with an undilated pupil. This standard observer may differ from any given human subject being exposed due to age or other characteristics, particularly if the subject’s pre-receptoral transmittance of the ocular media deviates significantly from the standard transmittance $\tau(\lambda)$ (see Annex A). Clearly then, the same light exposure may not produce the same retinal stimulus to all observers and information about the (presumed) pre-receptoral transmittance of the ocular media for the subjects should be reported whenever applicable.

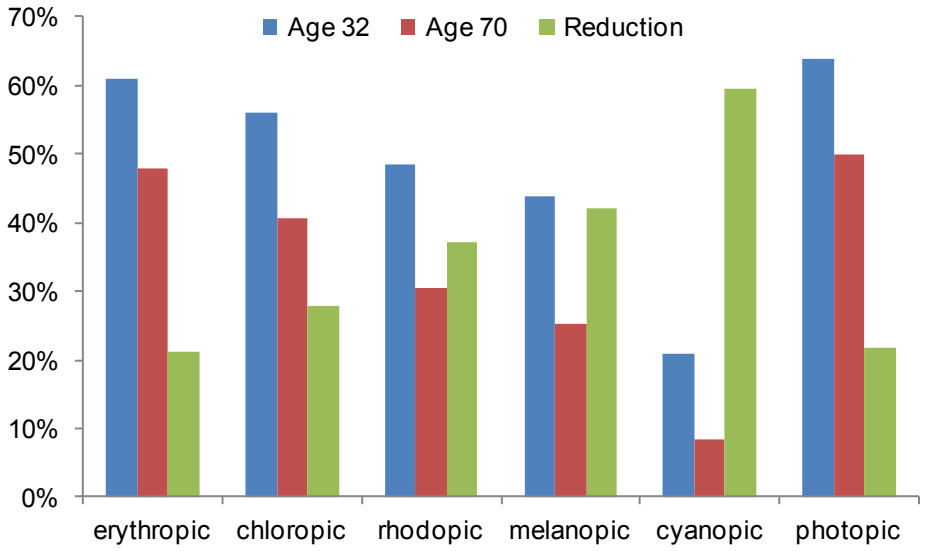
Some types of polychromatic lighting have broad spectral features. In this case, it may be possible to allow for ageing when estimating retinal stimuli with five simple percentage corrections to the five respective α-opic quantities. This is less accurate, however, for spectra which are selective across the photopigment wavelength ranges (e.g. sources with pronounced narrowband features), and the full SID would be needed to calculate the relative effects of age-related transmittance functions.

In the majority of cases it is preferable to report the SID, and factors relevant to the pre-receptoral transmittance, including age. These data should be sufficient to allow the reader to estimate the relative strengths of retinal stimuli for the five photopigments.

3.3 The impact of lens age

Deviating from the Workshop’s discussions, an example is given here to illustrate the impact of lens age. For additional details relating to the age-related lens model used, see Annex A. For the standard observer (32 year old) only 61 %, 56 %, 49 %, 44 %, and 21 % of the irradiance under equal energy illumination arrives at the retina, weighted according to the photopigment sensitivities lc, mc, r, z and sc, respectively. For a typical 70 year old, these figures reduce, particularly at the short wavelengths, to 48 %, 41 %, 31 %, 25 % and 8 % (see Figure 2).

As shown in Figure 2, photopic transmittance reduces less with age than the transmittance relating to the α-opic sensitivities, as the $V(\lambda)$ function is narrower and more concentrated at longer wavelengths than even the chloropic and erythropic functions (see also Figure 3), and so the reduction in visibility may understate the reduction in non-visual photoreception with age. Retinal photopic sensitivity was estimated by dividing $V(\lambda)$ by the standard observer transmittance function.



NOTE The irradiance is spectrally weighted for the relevant α-opic function. The percentage reduction (green) represents the change in the value at age 70 relative to age 32, the standard human observer age.

Figure 2 – Age-related reduction in the percentage of irradiance measured at the outer surface of the eye that reaches the retina (based on an equi-energy source)

3.4 Spectral sensitivity

The primary signal driving ipRGC firing and the downstream physiological and behavioural light responses is defined by several phototransduction processes. ipRGCs combine the melanopsin-driven photosensitivity of the ipRGC itself and the signals due to photoreception in the rods and cones in the ipRGC's network (Figure 1B).

Each mechanism of light detection has a distinct spectral sensitivity function; here it is defined by the spectral efficiency of the five human photopigments and the spectral transmission properties of the ocular media.

- Melanopsin is the photopigment of the ipRGCs. The available data indicate that the wavelength of peak sensitivity, λ_{max}, is around 480 nm (Hankins, 2002; Dacey, 2005; Peirson, 2006; Gamlin, 2007; Bailes, 2013). Human pre-receptoral filtering in the standard human observer shifts this towards around 490 nm.
- Rhodopsin is the photopigment of rod photoreceptors. It shows peak sensitivity at a wavelength, λ_{max}, around 498 nm (Bowmaker, 1980). Human pre-receptoral filtering shifts this towards somewhat longer wavelengths in the standard human observer, between 505 nm and 510 nm, which is the peak for scotopic sensitivity.
- Three cone opsins are the photopigments in human cones. Human S-cone opsin (cyanolabe) shows peak sensitivity at a wavelength, λ_{max}, around 420 nm; the M-cone opsin (chlorolabe) around 534 nm and L-cone opsin (erythrolabe) around 564 nm (Stockman, 2000; Bowmaker, 1980). Human pre-receptoral filtering in the standard non-visual human observer shifts these peaks towards 440 nm, 545 nm and around 570 nm to 575 nm, respectively.

The peak sensitivity of rhodopsin at around 500 nm is common to all mammalian species. Melanopsin, the photopigment of ipRGCs, appears similarly invariant across many species at around 480 nm. The adjustments for pre-receptoral filtering introduce differences between species. The human standard observer which has been selected at around 32 years of age adds around 10 nm to the peak wavelengths, and 20 nm for the human S-cone photopigment. For each photoreceptor, further lens-ageing introduces an additional shift to longer wavelengths of around 5 nm at 70 years of age, relative to the standard human observer.

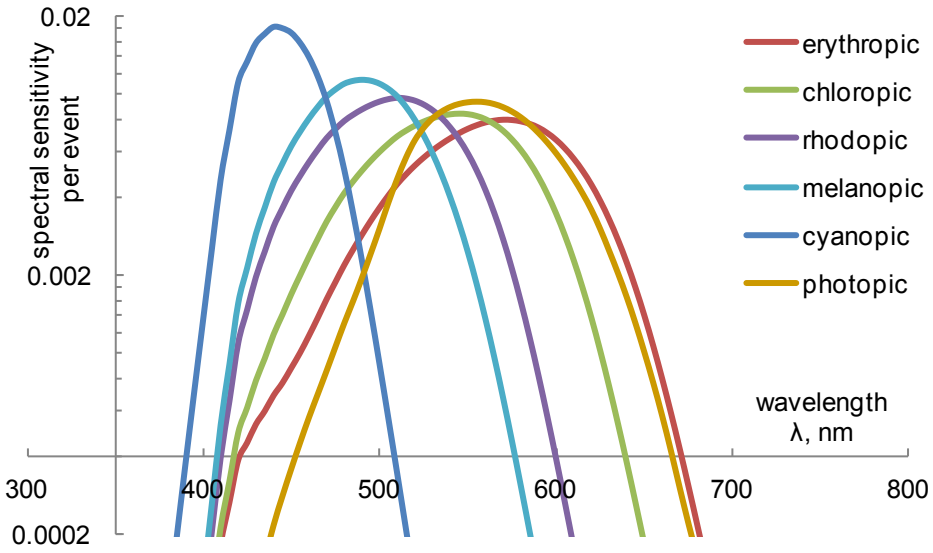


Figure 3 – Spectral sensitivity curves of the five human photopigments to irradiance at the outer surface of the eye of the standard observer and photopic spectral efficiency, normalized to equal area
(Data are included in Annex A)

A potential complication relating to the estimate of melanopsin's contribution to the spectral response property of ipRGCs in vivo is the suggestion that, like the rhabdomeric opsins of invertebrates, melanopsin may be bistable (Koyanagi, 2005; Melyan 2005; Panda 2005; Mure, 2007). Bistability affords rhabdomeric photopigments such as melanopsin the capacity to regenerate following light absorption through the absorption of another photon (Hillman, 1983). As the spectral sensitivity related the forward and reverse photoreactions can be different this could influence the spectral response properties of the receptor.

Whether mammalian melanopsin homologues are bistable and whether this bistability is biologically relevant remains to be determined (Mawad, 2008; Rollag, 2008; Papamichael, 2012). In either event, studies on mice indicate that this factor does not impact melanopsin's spectral response properties significantly under practical lighting regimes (Enezi, 2011; Brown, 2013).

Mammalian genomes typically contain several genes encoding spectrally distinct cone opsins. Humans, and other old world primates, are trichromatic, having three types of cones. Other mammals lack the chlorolabe/erythrolabe distinction, having a single cone opsin maximally sensitive in the middle of the human visible spectrum. There are also important species differences in the spectral sensitivity of the cyanolabe pigments. For example, many rodent retinas have a photopigment that is maximally sensitive to near-ultraviolet radiation.

The firing rate of ipRGCs may thus be influenced by five (or in the case of non-primates four) spectrally distinct photopigments (Panda, 2003; Rea, 2005), as illustrated in Figure 1B. It follows that the spectral sensitivity of downstream responses (and thus the spectral weighting function that should be applied during light measurement) will be determined by the manner in which the rod and cone channels are combined and interact with melanopsin phototransduction in ipRGCs. In fact, this interplay appears to be fundamentally context dependent, a feature clearly illustrated by studies of a well-understood ipRGC-driven response, the pupillary light reflex.

3.5 An example response: The pupillary light reflex

The pupillary light reflex (PLR) illustrates the complexity of a non image forming response in mammals including humans. The PLR is the involuntary reflex action of pupil constriction, following exposure of the eyes to light. It acts to control the aperture and thereby the amount of light reaching the retina.

Pupil area decreases with increasing irradiance over a range of intensities spanning around 9 orders of magnitude and is held steady when exposed to continuous and stable bright light (Bouma, 1962; Loewenfeld, 1993; Gamlin, 1995; Pong, 2000; Clarke, 2003).

A well characterized pathway links the sensory stimulus, visible irradiance entering the eye, to a motor output, pupil constriction. This pathway involves ipRGC signalling to the OPN. It is now recognized that rods, cones and melanopsin all participate in the PLR via ipRGCs. Their relative contributions change over time, even after 30 seconds of constant illumination.

There are similarities in the PLR stages between mammalian species (including between rodents, non-human primates and humans), with slight differences in spectral sensitivity. Figure 4 provides representative (not necessarily human) data to illustrate PLR dynamics.

The initial response to illumination is a rapid, robust pupil constriction predominantly driven by cones and to a lesser extent by rods. The size of this response, known as phasic pupil constriction, and the relative contribution of different photoreceptors, depends on the intensity and wavelength of the light stimulus.

In the next stage, the pupil gradually relaxes to a more dilated state. If the threshold for melanopsin activation is exceeded (i.e. sufficiently bright light) a steady state diameter will persist throughout light stimulation (Gamlin, 2007; Mure, 2009; McDougal, 2010). During this secondary post-phasic response the relative contribution of melanopsin increases and with prolonged illumination (greater than 3 minutes) the spectral sensitivity of the response is dominated by melanopsin.

ipRGCs are capable of prolonged and stable electrophysiological responses to light, which makes sustained pupil constriction possible. Pupil constriction will persist, for a time, in darkness following melanopsin activation in bright light. Often called the post-illumination pupil response, this is also consistent with melanopsin sensitivity (Kankipati, 2010).

Further support is provided by studies of the PLR in blind humans, pharmacological blockade of rods and cones in the monkey and two types of transgenic mice, lacking rods and cones (*rd/rd cl*) or lacking melanopsin (see also Lall, 2010).

In some blind humans, although the rapid phasic, or transient, rod-cone driven responses are necessarily absent, sustained and persistent pupil constriction can be seen (Zaidi, 2007; Gooley, 2012). These responses are consistent with melanopsin, as there is a significant latency in the PLR and the wavelength for peak sensitivity is 480 nm. Such people are naturally presumed to have intact ipRGCs.

Sighted monkeys, when subjected to a pharmacological blockade inhibiting responses from rods and cones, give similar results (Gamlin, 2007). The peak wavelength sensitivity is around 480 nm, consistent with similar findings in the (*rd/rd cl*) mouse (Lucas, 2001).

Conversely, in mice lacking melanopsin, full constriction is not attained even in bright light. With prolonged light exposure, the pupil returns to a dilated state – suggesting the sustained response of the ipRGCs is driven by melanopsin (Panda, 2002; Ruby, 2002; Lucas, 2014).

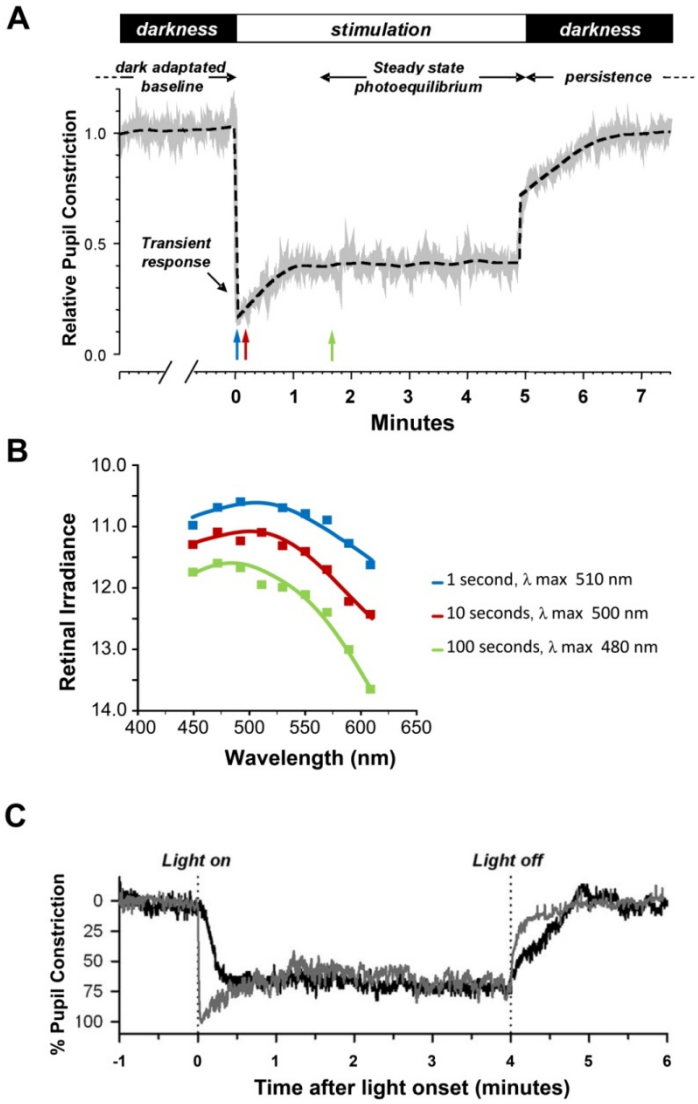


Figure 4 – Spectral sensitivity of half-maximal pupillary constriction in humans Graphs adapted from (Mure, 2009; McDougal, 2010; Gooley, 2012) and reproduced with permission (Lucas, 2014).

A. The PLR is composed of several different temporal components. The pupil shows a rapid, transient constriction during the first 1000 ms of light exposure. This is followed by a re-dilation to a sustained pupil diameter ('photoequilibrium') even during prolonged constant illumination. Following lights off, there is a slow melanopsin driven re-dilation of the pupil back to the dark-adapted rest state.

B. Retinal irradiance (log quanta/cm^2/s) to elicit half maximal constriction at nine wavelengths and durations of 1, 10, and 100 seconds (corresponding to the positions of blue, red and green arrows in A). Curves fitted using a mathematical combination of rod, cone, and melanopsin spectral sensitivities. The sensitivity of the response decreases with duration and is shifted towards shorter wavelengths.

C. Pupillary constriction in a sighted (gray) and a totally visually blind (black) subject. In the blind subject, lacking rods and cones but presumed to have intact ipRGCs, reactions were much slower. The transient responses were absent, but sustained steady state PLR and the persistent response following light-off were conserved.

3.6 Circadian and neurophysiological responses to light

The PLR example clearly shows there can be no single composite sensitivity function that describes this response under all conditions. Although it is sometimes possible to define a sensitivity function that applies in particular conditions, the sensitivity may be different for other types of systemic responses, and in other species, even when measured under the same conditions.

Cone inputs on the PLR decay quite rapidly, but their influence on SCN responses may be much more sustained (Gooley, 2010). For example, UV cones in mice have been shown to support a sustained SCN response (van Oosterhout, 2012), even in the absence of melanopsin. Variations in cone influence may arise from the differences in functional properties and targets in the brain between ipRGCs sub-classes (Allen, 2011; Brown, 2011).

At present, sub-classes (or types) of ipRGCs are not well described in humans. Studies in mice have found substantial variation in the nature and relative influence of different photoreceptors on ipRGC types and their signalling to the SCN and other central targets (Estevez, 2002; Schmidt, 2009). Using essentially identical conditions, there were remarkably different spectral responses in cells of various central targets.

These examples illustrate that the contribution of rods, cones and melanopsin to non-visual responses are likely to be affected by differences in the basic cellular properties and central processing that occurs within and between the central targets of ipRGCs and non-photosensitive retinal ganglion cell classes.

For these reasons, the composite spectral efficiency of one type of ipRGCs, if it could be reliably established for particular conditions, would not necessarily accurately predict the properties of any physiological response in those conditions.

Instead, predicting the physiological and behavioural effects of light may require a comprehensive description of the spectral sensitivity of the response itself for a range of conditions. Such a description would need to account for the complex interplay of the stimulus intensity, spectral composition, temporal dynamics, light exposure history and other circadian factors mainly dependent on the time of administration (e.g. circadian phase).

3.7 Consensus advice for researchers

Without a single spectral efficiency function or action spectrum that can be applied to all regulatory functions under all conditions, the advice for light measurement is necessarily complex. Going forward, the field may benefit greatly from rationalizing light measurements around a few evidence-based changes to current reporting practice.

Firstly, all laboratory and field studies should report the SID of light as experienced by subjects. This should be presented in an accessible form, such as a downloadable spreadsheet, so that others can calculate the stimuli for the five photoreception components. Inevitably for field studies, collecting and providing a comprehensive description of the exposures involves compromises and estimates; the reader should be able to understand what influence these may have numerically.

A range of low-cost spectrometers are available for this purpose, but it is important to highlight that in order for these to be useful, they should be calibrated regularly. Calibrations should be traceable to suitable national standards, and relate to the input optics used with the spectrometer. Wavelength calibration is achievable straightforwardly by reference to mercury emission lines, and should not be omitted. Details of the spectrometer make and model, and calibration date should be reported. Note that the CIE would also recommend other key characteristics be understood, such as slit function, ambient temperature, board temperature stability, linearity and stray light performance (i.e. light at a wavelength other than that which is intended to be measured reaching the detector) which can potentially lead to large errors with many CCD array spectrometers (Kostkowski, 1997).

The light experienced by the subject is determined not only by the nature of the light source, but also by the geometry and spectral qualities of reflective surfaces and media lying between

the light and the subject. The most direct way to capture this complexity is to measure the SID of the light falling on the subject's eye (i.e. nearby, in the plane of the eye). For completeness and for practical reasons, recording other aspects of the light exposure, such as the make and model of the light source, is also encouraged, but not as a substitute for calibrated measurements.

There are many advantages in reducing the SID to the five dimensions from Tables 1 and 2, reflecting the overlapping spectral sensitivities of the functional photopigments to corneal irradiance. Firstly, it is possible to recreate the effective irradiance for each of the photoreceptors without attempting to reproduce every aspect of an alternative study's SID. Secondly, comparing quickly across different studies becomes practical. At present a measurement of the full SID is needed to do this, but this reduced data would summarize the comparable aspects of the full spectral profile.

For facilitating comparisons and opening the literature up for meta-analyses, researchers should report their light exposures in the five quantities recommended in Tables 1 and 2. This would allow the literature to be mined to determine whether particular responses under specific circumstances can be adequately explained by a specific composite function of the components.

3.8 Consensus advice for industry and regulation

As described in earlier clauses, the amount of light in the environment affects a broad range of unconscious physiological systems. These regulatory effects of light have significant implications for the design of human environments (as well as those of domesticated animals). Light's effects on these biological processes can exert both beneficial and detrimental impacts on human health, performance, well-being, and safety.

For example, for workers on night shifts, light at work promotes alertness while also supporting the conscious perception of visual form, pattern, colour and motion needed to execute important job functions. For workers on the day shift, however, night-time light exposures can disrupt sleep. Between shift patterns appropriately timed light can assist in circadian realignment, but it is unlikely it can entirely eliminate the circadian disruption following a shift pattern change.

The amount, timing and spectral composition of light all contribute to its net effect on unconscious physiological systems. The responses also depend on the interactions with current state of these systems, which will reflect the accumulated effects of prior light history and the history of other relevant stimuli. The contribution of light exposures to circadian physiology should therefore be carefully considered in the design of spaces in which we work, live and sleep.

The brain contains a centralized self-supporting clock or endogenous circadian pacemaker. Through this pacemaker, light exerts a variety of positive effects on physiology. The 24-hour light-dark cycle generated by the earth's axial rotation is the major environmental time cue that resets the clock. Light information received in the eyes passes directly to the SCN and other central targets via a dedicated neural pathway, the retinohypothalamic tract (RHT). Each day the light-dark cycle adjusts the internal clock which in turn synchronizes the physiology, metabolism and behaviour controlled by the clock.

The vital role of the daily pattern of light and dark is easy to take for granted. When light information cannot be detected at all, for example in most totally blind people, the circadian pacemaker reverts to its self-sustaining non-24-hour period. The resultant clinical disorder is termed 'non-24-hour sleep-wake disorder'. Their clock period is remarkably stable but varies between individuals between 23,7 and 25,1 hours.

Progressively, the timing of many aspects of physiology and behaviour controlled by the circadian system becomes desynchronized from the 24-hour day and may become desynchronized from each other (for example the sleep-wake cycle, acute alertness and cognitive performance, the core body temperature rhythm, and melatonin and cortisol production).

Non-24-hour sleep-wake disorder is characterized by episodes of good sleep, followed by episodes of poor night-time sleep and excessive day-time napping, followed by good sleep and so on, as the non-24-hour circadian pacemaker cycles in and out of phase with the 24-hour social day (Lockley, 2007b). Temporarily, sighted people can experience similar circadian disruption following rapid east-west travel (‘jet lag’) or while working shift patterns.

Ocular light exposure also stimulates other non image forming responses. The spectrum of light that most strongly causes night-time melatonin suppression provided the first indication of a new photoreceptor in humans. In addition, light can improve subjective ratings of alertness, reaction times, reduces lapses of attention and changes brain waves to frequencies that specifically indicate a more alert state. Other known effects of light include increasing heart rate and core body temperature and stimulating morning cortisol production. Light has also been shown to have anti-depressant properties, particularly in the treatment of Seasonal Affective Disorder.

Activation of neurophysiological and behavioural responses by light is not always positive. For humans and other diurnal species, nocturnal exposure to light brighter than moonlight is arguably unnatural. Recently, in evolutionary terms, bright light would only usually occur during the day. It should come as no surprise that light exposure at night induces a ‘day-like’ physiology in diurnal animals (low melatonin, higher alertness, higher temperature and heart rate and the like), all of which may come at a cost which includes sleep deprivation. In some cases, well-being can be promoted by avoiding excessive evening light and, when practical, seeking complete darkness at night, for example to avoid activating the brain during rest and sleep.

A particular light exposure, whatever its magnitude and spectral composition, can have both beneficial and detrimental effects. Two opposing effects can even be present simultaneously in a single individual. Light which supports alertness and performance in the evening may cause melatonin suppression and circadian phase delay and reduce the robustness of circadian rhythms by reducing both the magnitude of oscillation in circadian processes and the degree of synchrony between them. It is thought that ill-timed light is probably responsible for an increased breast cancer risk in long-term night shift workers.

Reducing light levels can likewise exert both positive and negative effects. For the night-shift worker heading home after their night-time work, light-attenuating goggles might serve to minimize the adverse shifts in circadian timing resulting from exposure to the rising sun, but at the price of attenuating the alerting effects of light and increasing the risk of impaired driving (Lockley, 2007a).

Balancing the desirable and undesirable impacts of light or darkness requires care. Informed decisions need to be based on consideration of context and of all the effects of light on physiology, perception and cognition.

Such calculations can be a daunting challenge, all the more so because both basic and applied science in this area continues to progress rapidly. Simple prescriptions are as likely to do harm as good, and even experts are likely to have divergent ideas about best practices for a variety of specific situations.

How then to approach the design problem? The starting point should ideally be based on a detailed assessment of how light sources of known amount and spectral composition influence the output of the ipRGCs. However:

- Each of the five opsins has different spectral and temporal sensitivity properties.
- The contribution from each component differs between the multiple types of ipRGCs.
- The contribution from multiple ipRGC types differs between the target functional systems.
- There is feedback from the ipRGCs and from the target functional systems, which is well illustrated in the case of the pupillary light reflex.

As a result, the balance between the five spectral components may depend on, or be altered by, the amount and duration of the light, the prior light history, or an individual’s internalized

time of day. For this reason, it is not possible to provide a single action spectrum that describes all circadian and neurophysiological responses to light or in all circumstances.

If the objective is to minimize the activation of melanopsin-based circuits at night or to simulate night-time, the goal should be to keep irradiance as low as possible. There is no established threshold below which the non-visual systems are blind to light, so complete darkness may be ideal, where practical. Light of any visible wavelength can, in principle, activate the system. Since the relative sensitivity and persistency of these regulatory systems is reduced in the longer visible wavelength range, light sources should be biased toward longer visible wavelengths, to the extent consistent with other demands.

Conversely, if the objective is to maximize melanopsin-based photoreception, lighting conditions should reflect daylight, being bright and with a dominant proportion of blue and green wavelengths. This should be done sparingly if the individual would normally be asleep or should be preparing for sleep at a particular time of day, however day-like conditions should be the norm at other times of day. In practice, there are also many other requirements from the amount and spectrum of lighting, including safety and visual preference, which will need to be considered.

A particularly challenging situation is when people with different light exposure requirements are in the same environment. For example on the night shift in hospital, staff require appropriate light to maintain their own alertness and to be able to see patient skin colours, whereas a patient ideally requires complete darkness for optimum sleep.

4 CIE recommendations for photobiological quantities and units

As discussed previously, the use of new non-SI units and normalized spectral sensitivity functions, as proposed by the Workshop and set out in Annex B, is in direct conflict with the guidelines produced by the CIPM (International Committee on Weights and Measures) regarding the SI (the International System of Units) and is therefore not recommended by CIE. CIE recommends that all measurement quantities and their associated units are expressed in accordance with the SI; the use of non-SI units is strongly deprecated.

According to the present definition of the SI, a photobiological or photochemical quantity must be defined in purely physical terms as the quantity derived from the corresponding radiant quantity by evaluating the radiation according to its action upon a selective receptor. The quantity is given by the integral over wavelength of the spectral distribution of the radiant quantity weighted by the appropriate actinic action spectrum (BIPM, 2006, Appendix 3), with the action spectrum being a relative quantity (i.e. dimensionless, normalized to one at the peak). Except for photometric quantities, the unit of the photobiological or photochemical quantity is the radiometric unit of the corresponding radiant quantity. When giving a quantitative value, it is essential to specify whether a radiometric or actinic quantity is intended as the unit is the same.

In the case of the five photopigment-based spectral sensitivity functions considered by the Workshop, the CIE recommendation, which complies with SI guidelines, is to use quantities of the form 'α-opic spectrally-weighted flux', with corresponding units based on the watt (W). When quoting the result, the relevant spectral weighting function must also be quoted e.g.:

cyanopic flux = 1×10^6 W (using the s-cone spectral weighting function).

Table 2 – The photoreceptors of the human retina, their designation and formulae for α-opic irradiance, following the SI-compliant approach recommended by CIE

Photoreceptor	Photopigment (label, α)	Spectral efficiency, $s_\alpha(\lambda)$	Quantity (α-opic irradiance)	Quantity symbol ($E_{e,\alpha}$)	Unit symbol
s-cone	photopsin (sc)	cyanolabe	cyanopic irradiance	$E_{e,sc}$	$W \cdot m^{-2}$
m-cone	photopsin (mc)	chlorolabe	chloropic irradiance	$E_{e,mc}$	$W \cdot m^{-2}$
l-cone	photopsin (lc)	erythrolabe	erythropic irradiance	$E_{e,lc}$	$W \cdot m^{-2}$
ipRGC	melanopsin (z)	melanopic	melanopic irradiance	$E_{e,z}$	$W \cdot m^{-2}$
rod	rhodopsin (r)	rhodopic	rhodopic irradiance	$E_{e,r}$	$W \cdot m^{-2}$

CIE recommends that the α-opic irradiance is determined by convolving the spectral irradiance, $E_{e,\lambda}(\lambda)$ ($W \cdot m^{-2}$), for each wavelength, with the action spectrum, $s_\alpha(\lambda)$, where $s_\alpha(\lambda)$ is normalized to one at its peak:

$$E_{e,\alpha} = \int E_{e,\lambda}(\lambda)\, s_\alpha(\lambda)\, d\lambda \qquad (3)$$

where the corresponding units are $W \cdot m^{-2}$ in each case. To avoid ambiguity, the weighting function used must be stated, so, for example, cyanopic refers to the cyanopic irradiance weighted using the s-cone or $s_{sc}(\lambda)$ spectral efficiency function.

NOTE In order to compare actinic α-opic irradiance quantities with the corresponding photometric or radiometric quantity, the approach detailed in CIE TN 002 (CIE, 2014) should be followed.

Values for $s_\alpha(\lambda)$ can be calculated from the data given in Annex A, using $s_\alpha(\lambda) = N_\alpha(\lambda) / N_\alpha(\lambda_{max})$, where λ_{max} is the wavelength of peak sensitivity.

5 Irradiance toolbox for circadian and neurophysiological photobiology

The toolbox and user guide are available freely online with the review article (Lucas, 2014). A revised version of the toolbox accompanies this Technical Note, which allows the user to select SI compliant units recommended by CIE and avoid the use of non-SI units (downloadable at http://files.cie.co.at/784_TN003_Toolbox.xls).

The toolbox provides calculations of the five human α-opic equivalent lux values (or the five α-opic irradiances) together with photopic lux and unweighted irradiance and photon flux values, all of which are determined from the user's SID measurements (or some preloaded values). This allows the light stimuli from previous studies to be re-expressed in terms of the five new quantities.

It is expected that the user will have measurement data with a resolution of 1 nm or 5 nm. The input section asks for SID data in the visible wavelength range from 380 nm to 780 nm (378 nm to 782 nm for 1-nm data).

An option to select a standard and/or familiar spectrum can be used as a proxy for a spectral measurement. This might be used for comparison purposes, for example, with historic data where spectral information is only presented in this limited form. As idealized illuminants will rarely match the environmental conditions adequately in practice, spectral measurement data are required for the best results. A range of blackbody spectra and Gaussian narrowband, including effectively monochromatic, power distributions can be chosen.

Calculations are based on a 5-nm resolution. The sensitivities are defined by an opsin template (Dartnall, 1953; Govardovskii, 2000) with peak sensitivities to the nearest 1 nm, with a probable standard error of between 1 nm and 5 nm. Variations in pre-receptoral

transmittance of subjects from the standard observer may be considerable, and the function is based on data points measured at 10-nm intervals. The magnitude of errors in absolute measurements of light exposures with traceable calibrations are at least 5 % to 15 % in carefully controlled conditions (such as a light and temperature controlled laboratory), although relative measurements can produce greater accuracy in stable controlled conditions.

Consequently, there would be little advantage to calculations based on a 1-nm resolution in most applications. For convenience 1-nm measurement data can also be used, but it will not directly increase accuracy.

No standard units are being suggested for non-human photoreception, and note that the five equivalent lux definitions relate to a standard human eye (see below). It is recommended that light conditions are quoted as SIDs where non-human responses are studied, just as it is still recommended for humans.

The α-opic equivalent lux values allow for the absolute spectral transmittance of the pre-receptoral media for a standard observer. Age-related models for human lens transmittance are readily available (e.g. Pokorny, 1997), but to define a usable standard observer, age is also required. The age selected was 32, and this was based on the approximate average age from the data collected by Gibson and Tyndall (Gibson, 1923) which forms the basis for the photopic spectral luminous efficacy, or $V(\lambda)$.

It is important to understand that, although the light conditions may be identical, ageing of human lens will change the eye's transmittance. This will cause the sensitivity curves to shift towards higher wavelengths and reduce the total sensitivity, especially for the shorter wavelength photopigments. This reduction in sensitivity may be accompanied by a change in pupil dynamics with age.

Rather than have a standard spectral weighting function for every age, a better approach may be to express light conditions in terms of the five α-opic quantities, and calculate a separate percentage figure for the reduction in stimulus due to age for each photopigment (or increase for ages below 32). It would seem to be good practice if taking this approach, to note how both lens ageing and pupil size were taken into account.

The human sensitivity curves and the transmittance function derived from the lens model data from Pokorny and Smith (Pokorny, 1997) and Wyszecki and Stiles (Wyszecki, 1982) are given in Annex A (also see Figure 3 and Tables A.1 and A.2).

6 Discussion and interpretation

The following clause represents the CIE reporter's perspective on the significance of the Workshop outcomes. It is based upon themes covered at the Workshop but extended according to the reporter's personal views.

The Workshop published a toolbox containing non-SI compliant units (Lucas, 2014). As the CIE strongly deprecates the use of these units, an updated version of the toolbox is published alongside this Technical Note (downloadable at http://files.cie.co.at/784_TN003_Toolbox.xls). This will enable researchers to easily calculate the key non-visual quantities in SI compliant units, and make comparisons to measurements recorded in most of the comparable units that have been used in research on non-visual responses to light.

6.1 Discussion

The Workshop participants did not feel any approximate action spectrum could be given that indicates the first order impact of light on circadian rhythms. The advice section gives a rule of thumb for maximizing or minimizing circadian and neurophysiological effects of light.

The aggregate sensitivity of ipRGCs may depend on one or more photoreceptor type(s), other conditions and context. The conditions have been listed before (IES, 2008; CIE, 2004; NRCC, 2011), but bear repetition; non-visual sensitivity to light depends on:

- the light amount and spectrum,

- the timing, modulation and duration of exposure, and
- the accumulated effects of the prior light history of the individual.

As the accumulated effects of the prior light history also depend on the sensitivity to light of non image forming photoreception, the feedback in this system is often far from trivial. For example accumulated effects add considerable complexity for circadian phase shifting sensitivity to light, with two distinct types of phase resetting possible: 'strong' where the stimulus dominates in setting an independent new phase and 'weak' where the phase timing of the stimulus is important, i.e. the resetting combines with the original phase (Czeisler, 2007).

To anyone requiring circadian, neuroendocrine and neurobehavioural action spectra that apply in specific conditions, the Workshop has provided two clear messages:

- No single action spectrum is currently proven to mediate any individual non-visual response in all conditions
- New data are required where the measurement and presentation of light exposures used in experimental work needs to be calibrated, consistent and spectrally complete. Five new α-opic equivalent lux units and a spectral weighting calculation model are provided.

6.2 Interpretation: Working towards standards

CIE supports the consensus of the Workshop with the proviso that the SI compliant quantities and units set out in Table 2 should be used. Although the non-SI compliant IWCNP units set out in Table 1 produce results with similar magnitudes to photopic lux, there is no loss of information in using SI units as recommended by CIE. As stated, either approach produces important, convenient and unambiguous information about the stimulus at the outer surface of the eye.

Commerce understandably would welcome a standard action spectrum (or more than one) for non-visual responses to light in humans. The IWCNP consensus provides a detailed explanation why it is currently not possible. However, the CIE may consider their consensus as an important step forwards towards the goal of predicting non-visual responses to light stimuli. CIE (as well as other standards bodies) may also wish to consider adopting five spectral quantities as standard basis functions of light stimuli that bring about photobiological end-points. It should not be forgotten that these will need to be combined with the necessary information about an individual's current circadian phase and dynamic physiological state.

6.3 Interpretation: Providing advice on lighting practice

For the avoidance of doubt, it is worth reiterating here that the views expressed in Clause 6 (except for the first statement in 6.2) are the reporter's own views, and may not be the views of CIE or IWCNP.

The Workshop participants made no statements that link measurements of the five α-opic quantities to effects of light on health and physiology. They felt that the relationship between systemic regulatory effects and their causes, in the form of light exposures, is not currently well enough understood.

Recommendations for lighting practice in this area are complicated by the conflicting purposes of lighting. These conflicts arise between:

- Different non image forming (NIF) effects in one person
- NIF effects and vision in one person
- NIF effects in different people
- NIF effects in one person and vision in another
- NIF effects, vision and numerous other parameters familiar to lighting specialists, e.g. energy efficiency, colour rendering, glare,

where the term non image forming effects has been used in the list as shorthand for the effects of photoreception mediated by the ipRGCs in the widest sense.

For instance, darkness may be beneficial for vision where dark adaptation is required, but may not promote alertness, which could compromise safety or productivity.

Alternatively, lighting is necessary at night for staff in hospitals and care homes, but conflicts with dark night-time conditions suitable for sleep and circadian regulation in patients and residents.

Similar conflicts have not entirely frustrated the production of lighting standards in the past, but crucially circadian and neurophysiological effects relate closely to medical and safety factors. Clearly, this needs added caution, especially for vulnerable individuals, as well as situations, including building design and regulations, where daily lighting decisions are taken on behalf of others. Similar considerations apply to street lighting and other outdoor lighting, where the effects are not restricted to people.

6.4 Interpretation: Advice to governments and public health professionals

Light exposures and their effects on health and wellbeing are increasingly recognized as an important public health topic. We may not always realize the significant benefits and detriments light exposures produce, but for most of us, our exposure to light is strongly influenced by other people's decisions over lighting and the time we are expected to spend indoors. The young, old and sick depend greatly on others to regulate their light exposures, and hopefully to provide timely daytime access to the outdoors. It is probably far too easy for these needs to be overlooked or trivialized.

Governments regularly provide public health advice on diet and exercise. Much of that advice stands the test of time because it is based on strong scientific evidence, even whilst new findings are being continuously published. The science of non-visual effects of light is relatively young, but in terms of its relevance and the level of understanding of human physiology it provides, it has already reached a level of parity with these traditional areas:

- Light has proven influences on our bodies, arguably as profound as diet or exercise
- Leading researchers are increasingly interacting with the public, independently of professionals in public health bodies and governments

There is now a strong case to include 'light advice' in government sponsored health programmes. There is particularly a need to educate the public about the connection between circadian rhythms and exposure to light. Governments and public health bodies should be seen to endorse these important, established findings of science.

Annex A

Pre-receptoral transmittance and action spectra data

Table A.1 – Spectral values proposed by IWCNP for pre-receptoral transmittance $\tau(\lambda)$ and α-opic spectral efficiency functions of the five human photoreceptors, given as $\log_{10}(N_\alpha(\lambda))$

nm	Erythropic	Chloropic	Rhodopic	Melanopic	Cyanopic	$\tau(\lambda)$
380	−5,169	−5,105	−4,987	−4,980	−4,012	0,003
385	−4,925	−4,867	−4,743	−4,721	−3,723	0,005
390	−4,685	−4,631	−4,494	−4,452	−3,437	0,008
395	−4,448	−4,396	−4,238	−4,173	−3,156	0,017
400	−4,213	−4,160	−3,973	−3,885	−2,879	0,025
405	−3,977	−3,918	−3,695	−3,585	−2,603	0,053
410	−3,741	−3,672	−3,408	−3,279	−2,333	0,081
415	−3,579	−3,492	−3,188	−3,043	−2,141	0,133
420	−3,415	−3,304	−2,962	−2,805	−1,954	0,185
425	−3,349	−3,209	−2,835	−2,671	−1,875	0,225
430	−3,277	−3,104	−2,708	−2,538	−1,804	0,265
435	−3,226	−3,018	−2,610	−2,437	−1,768	0,299
440	−3,166	−2,925	−2,513	−2,339	−1,741	0,333
445	−3,118	−2,848	−2,442	−2,267	−1,746	0,357
450	−3,060	−2,769	−2,374	−2,200	−1,764	0,380
455	−3,001	−2,696	−2,317	−2,144	−1,803	0,400
460	−2,935	−2,624	−2,264	−2,093	−1,858	0,420
465	−2,866	−2,555	−2,216	−2,048	−1,932	0,441
470	−2,795	−2,489	−2,171	−2,008	−2,027	0,461
475	−2,728	−2,432	−2,136	−1,980	−2,150	0,477
480	−2,662	−2,378	−2,104	−1,958	−2,293	0,493
485	−2,603	−2,333	−2,080	−1,947	−2,461	0,505
490	−2,545	−2,291	−2,060	−1,943	−2,644	0,516
495	−2,491	−2,253	−2,043	−1,946	−2,841	0,529
500	−2,441	−2,219	−2,029	−1,958	−3,045	0,541
505	−2,393	−2,187	−2,020	−1,978	−3,256	0,553
510	−2,349	−2,159	−2,015	−2,007	−3,469	0,566
515	−2,312	−2,136	−2,018	−2,048	−3,685	0,576
520	−2,277	−2,117	−2,026	−2,098	−3,901	0,585
525	−2,247	−2,101	−2,041	−2,158	−4,116	0,594
530	−2,219	−2,089	−2,063	−2,227	−4,329	0,603
535	−2,194	−2,079	−2,092	−2,307	−4,538	0,612
540	−2,172	−2,073	−2,129	−2,397	−4,745	0,621
545	−2,153	−2,071	−2,175	−2,497	−4,947	0,631
550	−2,136	−2,073	−2,230	−2,609	−5,146	0,641
555	−2,122	−2,080	−2,296	−2,733	−5,343	0,651
560	−2,111	−2,092	−2,372	−2,869	−5,536	0,661
565	−2,104	−2,112	−2,462	−3,017	−5,726	0,669
570	−2,101	−2,137	−2,563	−3,174	−5,913	0,678
575	−2,102	−2,171	−2,677	−3,341	−6,098	0,685
580	−2,107	−2,211	−2,804	−3,514	−6,280	0,692

nm	Erythropic	Chloropic	Rhodopic	Melanopic	Cyanopic	$\tau(\lambda)$
585	−2,117	−2,260	−2,942	−3,691	−6,458	0,699
590	−2,131	−2,316	−3,090	−3,871	−6,634	0,706
595	−2,152	−2,382	−3,248	−4,054	−6,807	0,712
600	−2,179	−2,458	−3,412	−4,238	−6,978	0,718
605	−2,212	−2,543	−3,582	−4,422	−7,146	0,723
610	−2,252	−2,639	−3,756	−4,605	−7,311	0,728
615	−2,298	−2,746	−3,932	−4,787	−7,473	0,733
620	−2,352	−2,862	−4,108	−4,966	−7,633	0,738
625	−2,415	−2,990	−4,286	−5,145	−7,791	0,741
630	−2,486	−3,126	−4,463	−5,322	−7,947	0,745
635	−2,565	−3,271	−4,640	−5,496	−8,100	0,748
640	−2,653	−3,422	−4,814	−5,668	−8,250	0,752
645	−2,752	−3,579	−4,988	−5,838	−8,399	0,754
650	−2,859	−3,739	−5,159	−6,005	−8,546	0,757
655	−2,976	−3,903	−5,329	−6,171	−8,690	0,759
660	−3,101	−4,068	−5,496	−6,333	−8,832	0,762
665	−3,234	−4,233	−5,661	−6,494	−8,971	0,765
670	−3,374	−4,399	−5,824	−6,652	−9,109	0,767
675	−3,519	−4,565	−5,985	−6,808	−9,245	0,769
680	−3,670	−4,730	−6,144	−6,962	−9,379	0,771
685	−3,823	−4,893	−6,300	−7,113	−9,511	0,773
690	−3,979	−5,056	−6,455	−7,263	−9,641	0,774
695	−4,136	−5,216	−6,607	−7,410	−9,769	0,776
700	−4,294	−5,376	−6,758	−7,556	−9,896	0,777
705	−4,452	−5,533	−6,906	−7,699	−10,021	0,778
710	−4,610	−5,688	−7,052	−7,841	−10,144	0,779
715	−4,767	−5,842	−7,196	−7,980	−10,265	0,780
720	−4,923	−5,993	−7,339	−8,117	−10,384	0,781
725	−5,078	−6,143	−7,479	−8,253	−10,502	0,782
730	−5,231	−6,291	−7,617	−8,387	−10,619	0,783
735	−5,383	−6,437	−7,754	−8,519	−10,734	0,784
740	−5,533	−6,581	−7,888	−8,649	−10,847	0,785
745	−5,681	−6,723	−8,021	−8,777	−10,958	0,785
750	−5,828	−6,863	−8,152	−8,904	−11,069	0,786
755	−5,973	−7,001	−8,282	−9,029	−11,178	0,787
760	−6,117	−7,138	−8,410	−9,153	−11,285	0,787
765	−6,258	−7,273	−8,536	−9,275	−11,391	0,788
770	−6,398	−7,406	−8,660	−9,395	−11,495	0,788
775	−6,536	−7,538	−8,783	−9,513	−11,599	0,789
780	−6,673	−7,668	−8,904	−9,631	−11,700	0,789

NOTE 1 CIE recommends that the spectral efficiency functions, $s_\alpha(\lambda)$ are normalized to 1 at the peak in each case, for use in calculating α-opic flux or α-opic irradiance quantities. Thus values for $s_\alpha(\lambda)$ can be calculated as $N_\alpha(\lambda)$ / $N_\alpha(\lambda_{max})$, where λ_{max} is the wavelength of peak sensitivity.

NOTE 2 To convert to $\log_{10}(s_\alpha(\lambda))$, deduct the maximum value in each column from all the values in that column, for example:
Rhodopic at 440 nm = (−2,513) − (−2,015) = −0,498

NOTE 3 The values of $N_\alpha(\lambda)$ and $s_\alpha(\lambda)$ are included in the Toolbox that accompanies this report.

The five α-opic spectral efficiency functions in Table A.1. were published in the Workshop's review (Lucas, 2014), contained in the toolbox. They are based on an opsin template (Govardovskii, 2000) with the maximum sensitivity values listed in Clause 3.3. The other elements used to construct these action spectra are set out in the remainder of this annex. The data are also contained in the revised SI-compliant toolbox.

Model for the transmittance function $\tau(\lambda)$ for the standard human observer

To have the required consistency with $V(\lambda)$, the action spectra in Table A.1 include realistic values for total pre-receptoral spectral transmittance from 380 nm to 780 nm; such values are also implicitly included in the measurements by Gibson and Tyndall (Gibson, 1923), the primary data used to derive $V(\lambda)$. The derivation of those values, that are given in Table A.1 as $\tau(\lambda)$, is set out below. The Pokorny and Smith (Pokorny, 1997) model for an optical density function of the lens, D_{L}, is the basis for these (here D_{L} stands for T_{L} etc. in Pokorny, 1997) Their original model also allows for changes with age x as follows:

$$D_{\mathrm{L}} = D_{\mathrm{L1}}\,(1 + 0.02(x - 32)) + D_{\mathrm{L2}} \quad \text{for 20 years} < x < 60 \text{ years, and} \tag{A.1}$$

$$D_{\mathrm{L}} = D_{\mathrm{L1}}\,(1.56 + 0.0667(x - 60)) + D_{\mathrm{L2}} \quad \text{for } x \geq 60 \text{ years,} \tag{A.2}$$

and a dilated pupil implies a 14 % reduction in the total optical density of the lens, D_{L}.

Table A.2 – Age variant D_{L1} and invariant D_{L2} optical density components for pre-receptoral transmission models of the human eye

Wavelength (nm)	Toolbox model		Pokorny, 1997	
	D_{L1}	$D_{L2} + D_{RL}$	D_{L1}	D_{L2}
380	0,800	1,800	No data	
390	0,700	1,400		
400	0,600	1,000	0,600	1,333
410	0,510	0,583	0,510	0,770
420	0,433	0,300	0,433	0,354
430	0,377	0,200	0,377	0,116
440	0,327	0,150	0,327	0,033
450	0,295	0,125	0,295	0,005
460	0,267	0,110	0,267	-
470	0,233	0,103	0,233	-
480	0,207	0,100	0,207	-
490	0,187	0,100	0,187	-
500	0,167	0,100	0,167	-
510	0,147	0,100	0,147	-
520	0,133	0,100	0,133	-
530	0,120	0,100	0,120	-
540	0,107	0,100	0,107	-
550	0,093	0,100	0,093	-
560	0,080	0,100	0,080	-
570	0,069	0,100	0,067	-
580	0,060	0,100	0,053	-
590	0,051	0,100	0,040	-
600	0,044	0,100	0,033	-
610	0,038	0,100	0,027	-
620	0,032	0,100	0,020	-
630	0,028	0,100	0,013	-
640	0,024	0,100	0,007	-
650	0,021	0,100	0,000	-
660 to 780	log linear	0,100	No data	

To extend the values to cover 380 nm to 780 nm, it can be observed that between 400 nm and 560 nm the D_{L1} values exhibit a log-linear relationship and above 600 nm the D_L values appear physically unachievable even for internal transmittance of the ocular media, and certainly for pre-retinal eye transmittance under normal conditions, as explained below.

A sharp corner in the transmittance functions produced by the model at 460 nm does not appear in other data, and could distort the adjusted sensitivity functions of photopigments near to this wavelength, particularly the cyanopic and melanopic functions. A comparison to other transmittance data also suggests the transmittance at around 400 nm wavelengths is too low compared with relatively young adult lenses.

The following modifications have been made, and Table A.2 illustrates how the toolbox differs from the original model:

- Intermediate points are derived by interpolation
- Wyszecki and Stiles' (Wyszecki, 1982) D_{L2} from 400 nm and 420 nm are reinstated
- Values below 400 nm are derived by visual extrapolations of D_{L1} and D_{L2}
- D_{L1} values above 560 nm are, iteratively, $D_{L1}(\lambda$ +10 nm)/ $D_{L1}(\lambda) = D_{L1}$(560 nm)/ D_{L1}(550 nm)
- A floor of 0,1 plus smoothing from 420 nm to 470 nm is applied to D_{L2}

The resulting spectral transmittance functions are consistent with other measured data (Barker, 1991; Kessel, 2010), for example see Figure A.1. Finally, a standard observer aged 32 and the undilated pupil option were selected for consistency with the $V(\lambda)$ test subjects. Conveniently, but by chance, the model equation at age 32 simplifies to:

$$D_L = D_{L1} + D_{L2}. \tag{A.3}$$

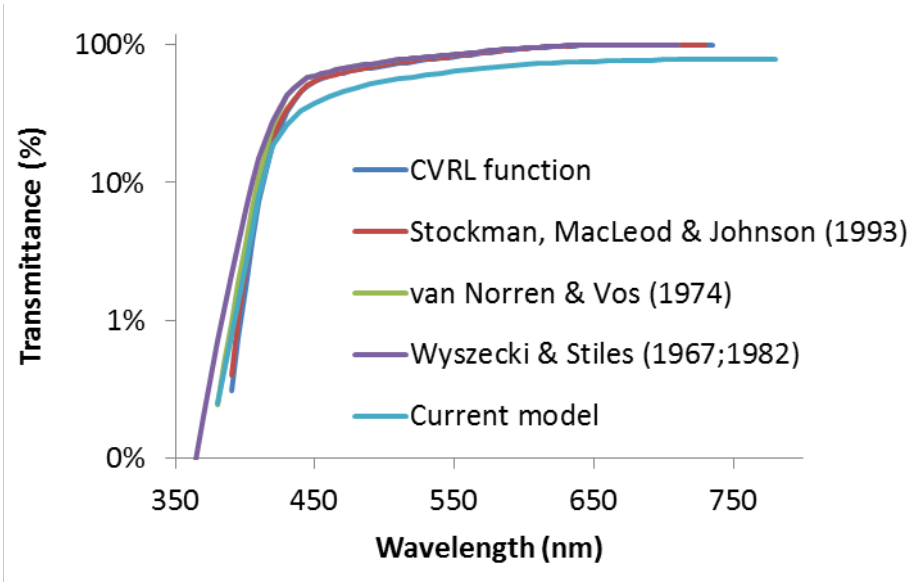


Figure A.1 – "Current model" for $\tau(\lambda)$ compared to existing models, age x = 32. The values are broadly the same, but do not tend asymptotically to 100 %. (Includes data from Stockman, 1993; van Norren, 1974; Wyszecki, 1982) Reproduced with permission (Lucas, 2014)

Maximum transmittance

The maximum transmittance (relating to the 0,1 floor in optical density) is consistent with total Fresnel reflective losses of the eye when in air (the natural environment in vivo), which are often overlooked, and non-vanishing internal absorption, both implicitly present in $V(\lambda)$.

By incorporating this floor in D_{L2}, the model includes a shortcut for the total pre-receptoral optical density equivalent, D_{PR}, for deriving the resulting transmittance, τ, as follows:

$$-\log_{10}(\tau) = D_{PR} \approx D_{L} + D_{RL}, \tag{A.4}$$

where D_{RL} is the optical density of reflective losses due to reflectance, ρ, so that:

$$D_{RL} = -\log_{10}(1 - \rho). \tag{A.5}$$

Self-screening

The incident light absorbed by the receptor depends on the peak axial optical density, effectively broadening the sensitivity curves. The sensitivity template has been adjusted to allow for this self-screening effect.

The mean values of photopigment peak axial optical density were taken to be approximately 0,40 for the rods, 0,30 for the S-cones and 0,38 for the other cones (Lamb, 1995; Stockman, 1999; Stockman, 2000). The low concentration of melanopsin, which also lies in the optical paths to the rods and cones, is not thought to appreciably modify the sensitivity curves.

Annex B

Terminology proposed by the Workshop

The use of new non-SI units and normalized spectral sensitivity functions, as proposed by the Workshop and set out below in definitions B.2, B.3, B.4 and B.7, is in direct conflict with the guidelines produced by the CIPM (International Committee on Weights and Measures) regarding the SI (the International System of Units) and is therefore not recommended by CIE. CIE recommends that the five α-opic measurement quantities set out below and their associated units are expressed in accordance with the SI; the use of non-SI units is strongly deprecated. This is also in accord with the ISO/IEC Directives (ISO/IEC, 2011) which also insist on the use of SI units.

According to the present definition of the SI, a photobiological or photochemical (actinic) quantity is defined in purely physical terms as the quantity derived from the corresponding radiant quantity by evaluating the radiation according to its action upon a selective receptor. The actinic quantity is given by the integral over wavelength of the spectral distribution of the radiant quantity weighted by the appropriate actinic action spectrum (BIPM, 2006, Appendix 3). The action spectrum is a relative quantity; it is dimensionless. Except for photometric quantities, the unit of the photobiological or photochemical quantity is the radiometric unit of the corresponding radiant quantity. When giving a quantitative value, it is essential to specify whether a radiometric or actinic quantity is intended, as the unit is the same.

B.1
α-opic
relating to the specified opsin-based human photopigment, denoted by α

EXAMPLE cyanopic: relating to the photopigment S-cone photopsin (α = “sc”).

Note 1 to entry: α represents one of five prefixes, set out in Table 1 of this report.

B.2
α-opic equivalent luminous flux ***(non-SI quantity)***
spectrally-weighted flux, where the spectral efficiency is specified by the prefix and is normalized such that flux with an equi-energy spectral power distribution producing one lumen also produces one α-opic equivalent lumen

Note 1 to entry: The CIE recommendation, which complies with SI guidelines, is to use the quantity ‘α-opic spectrally-weighted flux’, with the unit watt (W). When quoting the result, the relevant spectral weighting function must also be quoted e.g.:
cyanopic flux = 1×10^6 W (using the s-cone spectral weighting function).

Note 2 to entry: α-opic equivalent luminous flux is expressed in α-lm *(non-SI unit).*

B.3
α-opic equivalent illuminance ***(non-SI quantity)***
spectrally-weighted irradiance produced on a surface of area 1 m^2 by a spectrally weighted flux of 1 α-lm uniformly distributed over that surface

Note 1 to entry: The CIE recommendation, which complies with SI guidelines, is to use the quantity ‘α-opic spectrally-weighted irradiance’, with the unit watt per metre squared ($W \cdot m^{-2}$). When quoting the result, the relevant spectral weighting function must also be quoted e.g.:
cyanopic irradiance = 1×10^6 $W \cdot m^{-2}$ (using the s-cone spectral weighting function).

Note 2 to entry: α-opic equivalent illuminance is expressed in α-lx or α-$lm \cdot m^{-2}$ *(non-SI units).*

B.4
α-opic spectral efficiency, <of a monochromatic radiation of wavelength λ>
(not consistent with SI)
$N_\alpha(\lambda)$
spectral sensitivity to irradiance, incident at the eye’s outer surface, of the five human photopigments; the quotient of radiant flux at wavelength λ to that at an arbitrary fixed

wavelength λ_{ref}, such that both produce an equal photoreceptor activity attributable from the specified photopigment, normalized so that the summation of $N_\alpha(\lambda)$ over the wavelength range 380 nm to 780 nm, in steps of 1 nm, is equal to 1.

Note 1 to entry: The five probability-normalized $N_\alpha(\lambda)$ functions are in other respects analogous to *spectral luminous efficiency*, e.g. $V(\lambda)$, which is normalized to 1 at 540 THz, and the values are tabulated in Annex A of this report.

Note 2 to entry: The CIE recommendation is that the magnitude (rather than the area) of photobiological action spectra should be normalized to unity, normally at the peak, so that they represent the appropriate relative spectral weighting as a function of wavelength; other normalization methods are not recommended.

Note 3 to entry: Further derivative definitions of the proposed α-opic equivalent luminous flux are omitted for brevity.

Note 4 to entry: The α-opic spectral efficiency is dimensionless (unit 1).

B.5
ipRGCs
intrinsically photosensitive retinal ganglion cells

B.6
non-visual responses
non image forming responses
physiological and photobiological responses mediated by the ipRGCs which are broadly distinct from visual perception

B.7
non-visual spectral efficacy constant ***(not required for SI action spectra calculations)***
K_N
constant used to calculate α-opic equivalent luminous flux from α-opic spectral efficiency functions

Note 1 to entry: The value for the non-visual spectral efficacy constant is found from the equivalence condition in definition B.2, which can be expressed as follows:

$$K_N \int \Phi_{e,\lambda}(\lambda) N_\alpha(\lambda) \mathrm{d}\lambda \,/\, \alpha\text{-lm} = K_m \int \Phi_{e,\lambda}(\lambda) V(\lambda) \mathrm{d}\lambda \,/\, \mathrm{lm}$$

for a uniform spectral flux $\Phi_{e,\lambda}(\lambda)$, i.e. an equi-energy spectrum.

$K_N \approx 73\,000$ α-lm·W^{-1} for any value of α.

Note 2 to entry: The use of this constant is only relevant for the non-SI units described above.

Note 3 to entry: CIE recommends that if it is required to make a link between a photobiological quantity (such as α-opic flux) and the corresponding photometric or radiometric quantity, the approach detailed in CIE TN 002 (CIE, 2014) should be followed.

Note 4 to entry: The non-visual spectral efficacy constant is expressed in α-lm·W^{-1}.

B.8
melanopsin
photopigment responsible for the intrinsic photosensitivity of ipRGCs, both in humans (α = “z”) and in many other animals

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