Oxford 18th October 2013

Irradiance Toolbox

User Guide

Robert J Lucas[1], Stuart N Peirson[†2], David Berson[3], Timothy Brown[1], Howard Cooper[4], Charles A Czeisler[5], Mariana G Figueiro[6], Paul D Gamlin[7], Steven W Lockley[5], John B O'Hagan[8], Luke L A Price[†8], Ignacio Provencio[9], Debra J Skene[10], George Brainard[11]

[†]For technical correspondence, contact: stuart.peirson@eye.ox.ac.uk, Luke.Price@phe.gov.uk

[1]Faculty of Life Sciences, University of Manchester, Manchester M13 9PT, UK.
[2]Nuffield Laboratory of Ophthalmology, Nuffield Department of Clinical Neurosciences, University of Oxford, Headley Way, Oxford, OX3 9DU, UK.
[3]Department of Neuroscience, Brown University, Box G-LN, Providence RI, USA.
[4]INSERM 846 Stem Cell and Brain Research Institute, Department of Chronobiology 18 Avenue du Doyen Lépine 69500 Bron France.
[5]Division of Sleep Medicine, Harvard Medical School, and Division of Sleep Medicine, Department of Medicine, Brigham and Women's Hospital, Boston, MA, USA.
[6]Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY, 12180, USA
[7]Department of Ophthalmology, University of Alabama at Birmingham, Birmingham AL 35222, USA.
[8]Public Health England, Chilton, Didcot, Oxfordshire OX11 0RQ, UK.
[9]Department of Biology, University of Virginia, Charlottesville, VA, USA.
[10]Faculty of Health and Medical Sciences, University of Surrey, Guildford GU2 7XH, UK.
[11]Department of Neurology, Thomas Jefferson University, Philidelphia, PA, USA.

CONTENTS

The primary function of this toolbox application is to calculate effective illuminance for each of the 5 photopigments in the human eye, based upon accurately measured spectral power distributions. The 'Toolbox' worksheet automatically calculates these quantities from simple information provided by the user. For those who prefer to calculate these quantities for themselves, the relevant spectral sensitivity functions are provided in the separate worksheet labelled 'Reference' and a detailed description of the calculation appears in **Appendix 1** of this user guide. In addition, the application provides a number of other tools which may be of use for photobiologists.

The instructions in this document provide an overview of the Irradiance Toolbox application and details of the methodology used for the calculations. The Excel application is written in Excel 2010, running on Windows 7 on PC, and saved in .xls format for backward compatibility. Cosmetic differences may occur given different Office versions, operating systems or platforms. The calculations include no macros to minimise security risks and to ensure (hopefully) the application works on most systems. The toolbox is a human photoreception model. Separate models should always be used for animal studies to represent differences in pre-receptoral and receptoral spectral properties.

This work derives from 1st International Workshop on Circadian Neurophysiological Photometry and from previously unpublished work at University of Oxford.

A) BASIC USE

Cells coloured **blue** are unlocked, and enable user input. These are described sequentially below. Other cells are locked to prevent calculations based on user-input from being altered and to help protect against errors. In addition, some cells will only accept a limited range of values. Values outside these ranges are prevented as the results obtained will be inaccurate. Some cells also present an input message when activated, providing further information regarding the input to the cell. The position of these messages may sometimes cover regions of the worksheet, and as such, these can be moved by clicking and dragging the message to a more suitable location – a large blank area has been provided for this purpose next to the inputs.

Title and printing
This is provided for reference, so that if data is printed or saved, a reference or description of the experimental conditions can be included. The toolbox will print onto 2 sides of A4, and the title is duplicated on page 2.

1. Select mode (input)
The Irradiance Toolbox can be used in either of three modes – '***1nm'***, ***'5nm'*** or '***approximate'***. In '1nm' and '5nm' mode, irradiance measured as an exact spectral power distribution by the user (incident on the surface of the eye) is entered by the user in column AH and shown as used for calculations in column U (in $\mu W/cm^2/(5nm)$) – all the values in this range must be entered, or set to zero if appropriate. The toolbox works on 5 nm resolution, but a 1 nm resolution spectral power distribution (SPD) option is provided for convenience. The user does not need to modify their data, it will be converted automatically into 5nm resolution data, for example, by summating the five values 488 nm to 492 nm, inclusive measured in $\mu W/cm^2/nm$ to give the value for 490 nm. As a result of this summation, when using 1 nm resolution, data should ideally be entered from 378-782 nm, rather than 380-780 nm although in most cases the 380-780 nm data will give nearly identical answers. Alternatively, an 'approximate' mode may be used, where it is assumed that the SPD of the light source is approximated by a standard spectral power distribution (in **Section 2**, below).

WARNING: If 'approximate' mode is used, differences between the assumed and actual spectral power distribution will occur leading to reduced accuracy, particularly for broader, complex spectra from incandescent, fluorescent and white LED sources. Wherever possible, 'exact' mode should be preferred, and measurements should be made using a calibrated spectrophotometer. We recommend that illuminance values calculated using the approximate mode are clearly marked as 'estimates' in any published work.

2. Details of light measurement (inputs)
This section defines the **light source, quantity** and **units** which are used for subsequent calculations. These inputs are only needed for calculations in the 'approximate' mode.

Light source
If 'approximate' mode is chosen, then an appropriate light source should be chosen from the drop-down list, which will determine the spectral power distribution (SPD) used for subsequent calculations. The SPD of the light source currently in use is plotted in the upper graph on the Toolbox application in blue. As noted above, for accuracy it is strongly recommended that exact mode is used based upon a calibrated spectral power distribution (SPD) measurement. Otherwise, the standard illuminant functions provided may not accurately reflect the light source in use, providing a potential source of error. Examples of these are shown as relative spectral power distributions (RSPDs) in **Figure 2.1** and described below:

A Incandescent. Based on the CIE standard illuminant A [S1]. Illuminant A represents an incandescent tungsten filament lamp. This corresponds to a blackbody temperature, T = 2856 K.

D Daylight. Based on the CIE standard illuminant D_{65} [S1]. This corresponds to a blackbody correlated colour temperature (CCT) of around 6500 K, with atmospheric filtering.

F Fluorescent. This is based on a fluorescent light source, corresponding to the CIE standard illuminant F11 (CCT = 4000 K), [S1].

L White LED, an example comprising a blue LED combined with a yellow phosphor. CCTs of this type of illuminant can vary considerably. (CCT ≈ 4730 K) NB: Not a CIE standard illuminant.

N Narrowband (including 'monochromatic'). This enables narrowband light sources, such as narrow band-pass filters and single-colour LEDs to be modelled. SPDs are based on a Gaussian distribution with user defined peak wavelength and full-width half-maximum (FWHM) values. These details are entered in **Section 3**, below. For many 'monochromatic' filters used in photobiological research, FWHM is typically ~10 nm. Due to the integration range used for subsequent calculations, values are limited to 400-750 nm for peak wavelength and 5-50 nm FWHM.

B Blackbody radiator (also see **Section 3** instructions). This provides an SPD based on a blackbody radiator of defined colour temperature (see **Figure 3.2**). Colour temperatures between 2,000-20,000 K can be used.

E CIE standard illuminant E is an equal-energy radiator [S1], with equal spectral irradiance across the 380-780 nm range. This provides a useful theoretical reference, and is used to relate equivalent α-opic lux values to photopic lux (see **Section 5**, below). For an equal energy source 1 photopic lux implies 1 equivalent α-opic lux (simultaneously for each photoreceptor, labelled "α", based on a standard observer of 32 years of age).

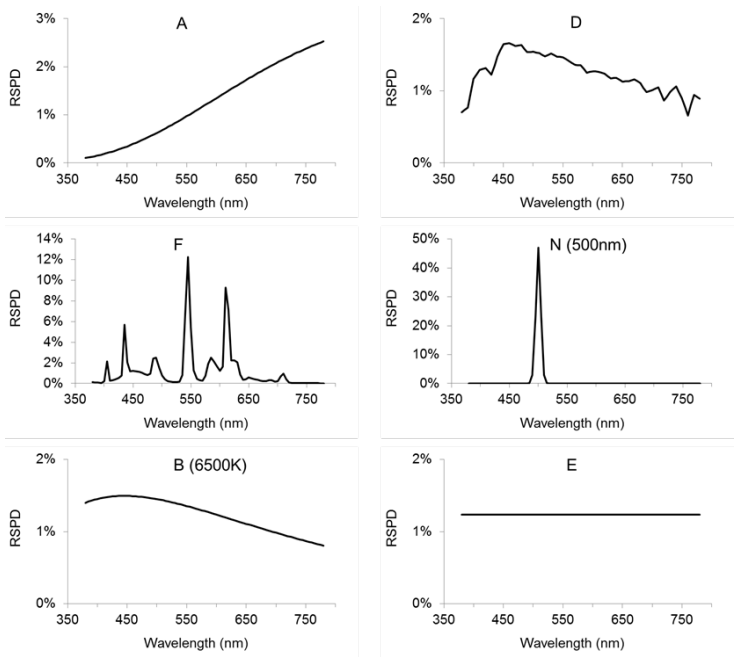

Figure 2.1. Example relative spectral power distributions, including incandescent (A), daylight (D), fluorescent (F), narrowband (N), blackbody (B) and equal-energy radiator (E). Narrowband sources require a peak wavelength and bandwidth (in this example 10 nm FWHM, full width at half maximum). Blackbody sources require a temperature to be specified.

Units

This box specifies the unit of light that is to be used for subsequent calculations. The drop-down menu provides three options:

- **L** lux (lumens per square metre or lm/m^2)
- **P** Power ($\mu W/cm^2$)
- **Q** Log quanta (log_{10} photons/cm^2/s). Note: log quanta are used due to the vast difference in scale that non-log values introduce. 12.2 log_{10} quanta equals exactly 10 times 11.2 log_{10} quanta *etc.*

Amount

The quantity of light used for subsequent calculations. This is a non-spectral measure (i.e. a single value), in the unit as defined in the previous box.

For example, to enter 100 lux of fluorescent light (based on an approximated standard fluorescent spectral power distribution), then these three cells should be filled out as follows:

Light source	F
Units	L
Amount	100

3. Additional light source parameters (inputs)

If a Narrowband (N) or Blackbody (B) light source is selected, then additional parameters are required to define the light source.

Narrowband: For Narrowband light sources, a peak wavelength is required (between 400-750 nm) and a full-width half-maximum (FWHM, between 5-50 nm). The effects of these parameters are illustrated in **Figure 3.1** below.

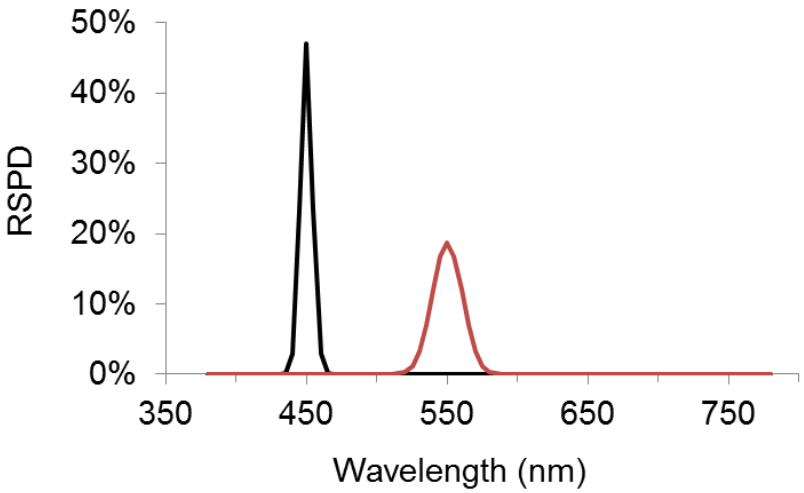

Figure 3.1. Narrowband light sources. Comparison of relative spectral power distributions (RSPD) for a blue laser with a 450 nm peak, 10 nm FWHM (black) and a green light source, 550 nm peak, 25 nm FWHM (red). Note the change in FWHM results in a wider spectral peak.

Blackbody: For blackbody light sources, the chosen blackbody temperature in kelvins must be between 2,000-20,000 K. An illustration of the effects of blackbody temperature on the spectrum is shown in **Figure 3.2** below. The peak emission of the chosen temperature is also shown, within the 380-780 nm range. Note, for temperatures below 3730 K this peak is >780 nm and for temperatures over ~7575 K this peak is <380 nm. For values outside this 3730-7575 K range a "n/a" error will be shown for peak spectral irradiance.

Blackbodies emit light with a spectral distribution that depends on their temperature. The colour of the light from a blackbody is strongly related to its temperature in kelvins. Correlated colour temperatures are calculated for other illuminants based on the blackbody that emits light with the 'most similar' colour, based upon colour-matching coordinates. Users should be aware that although many light manufacturers state correlated colour temperatures (CCT), these are not blackbody temperatures, and can be misleading. A 5000 K fluorescent lamp does not produce the same spectrum as a blackbody radiator at 5000 K; it may not even be a similar perceptual colour. The 'blackbody' feature of the toolbox works only with true blackbody radiators, for which the true colour temperature must be known.

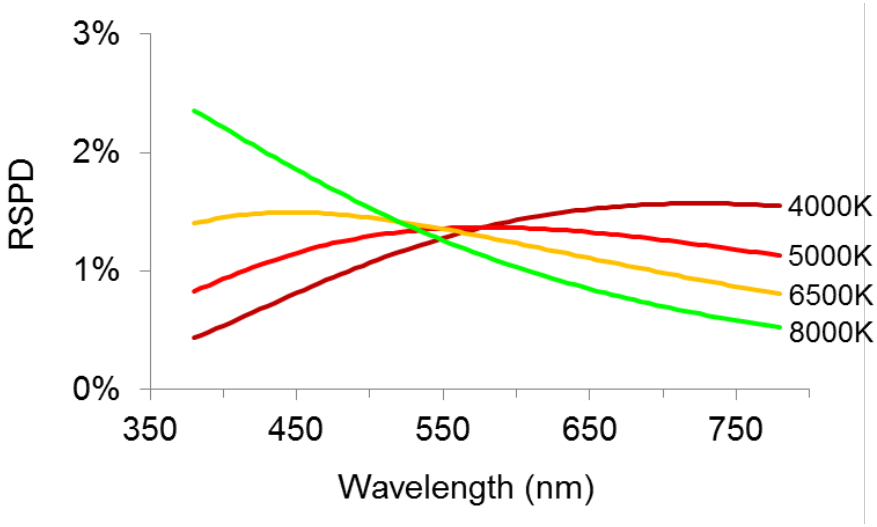

Figure 3.2. Blackbody light sources, illustrating the shift from long to short wavelengths with increasing temperature in the relative spectral power distributions over the range 380-780 nm.

4. Photopic illuminance (output)

This section provides an output in photopic illuminance based upon the values entered in **Section 1**, and, if approximate mode applies, **Sections 2-3**. If 'Units' in **Section 2** is set to Lux (L), this value will be identical to the value entered for 'Amount'. In 'exact' mode 'Units' and 'Amounts' inputs are not used, and this output will convert the measured spectral power distribution into a lux value based on the human photopic sensitivity function, V(λ).

5. Human retinal photopigment complement (outputs)

The primary function of this toolbox is to calculate equivalent "α-opic" illuminance values for each of the 5 photopigments in the human eye (λ_{max} values based on Dartnall et al. [S2], with full absorption curves based on Govardovskii et al., [S3]). This section provides a weighted output, based on the 5 photopigments of the human eye, corrected for pre-receptoral filtering (shown in **Figure 5.1,** and detailed in **Appendix 1**). Furthermore, the incident light absorbed by the receptor depends on the peak axial optical density, effectively broadening the sensitivity curves. To account for this self-screening effect, the sensitivity template is also adjusted based on the optical density of photopigment. The mean values of photopigment optical density at peak absorptance were taken to be approximately 0.40 for the rods, 0.30 for the S-cones and 0.38 for the other cones [S4-S6]. It should be noted that these values are based on a 10 degree visual field, and the optical density may vary in the peripheral retina. Due to the low pigment concentration and lack of specialised membrane structures in ipRGCs, the presence of melanopsin is not thought to appreciably modify the sensitivity curve in the same manner.

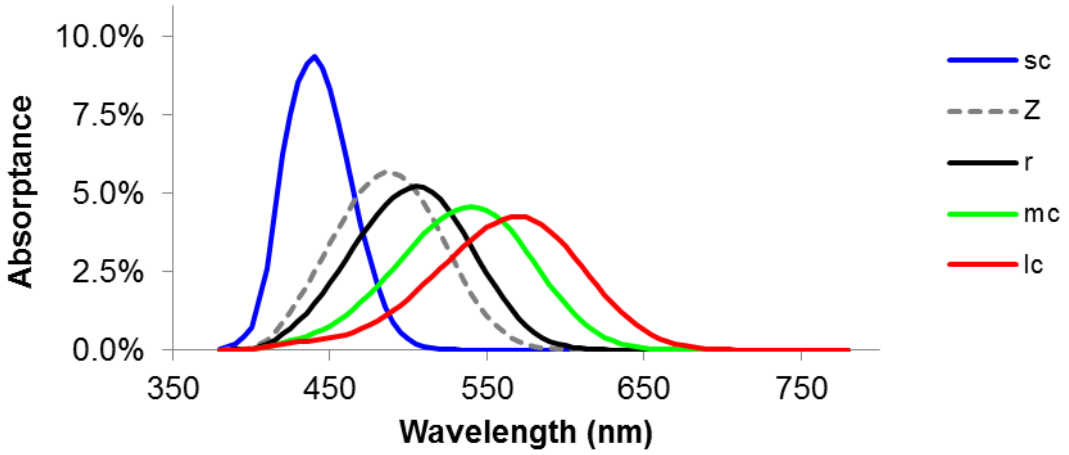

Figure 5.1. Spectral absorptance of human retinal photoreceptors, corrected for pre-receptoral filtering. All spectra are normalised to give an integrated area of 100%.

This output is given in our suggested new photometric units equivalent α-opic lux, where α defines the photopigment. These values are provided to help place these measurements into the context most familiar with most biological researchers (*i.e*. lux values). Moreover, this enables the sensitivity of each photopigment channel to be addressed independently. This results in 5 measurement output values, corresponding to the human retinal photoreceptor complement. An equation for equivalent α-opic illuminance is provided in **Appendix 1**; the 5 versions are summarised in **Table 5.1**:

Table 5.1. Photopigment complement of the human retina used for weighted outputs

Symbol	Prefix	Sensitivity	λ_{max}	α in $N_\alpha(\lambda)$	Curve
E_{sc}	Cyanopic	S cone	419.0	sc	$N_{sc}(\lambda)$
E_z	Melanopic	Melanopsin	480.0	z	$N_z(\lambda)$
E_r	Rhodopic	Rod	496.3	r	$N_r(\lambda)$
E_{mc}	Chloropic	M cone	530.8	mc	$N_{mc}(\lambda)$
E_{lc}	Erythropic	L cone	558.4	lc	$N_{lc}(\lambda)$

The equations used to calculate these equivalent α-opic illuminance values are set to ensure that equivalent α-opic lux values are always identical to photopic lux for a theoretical equal-energy

radiator (option E in **Section 2**), based upon a 32 year old standard observer (with an undilated pupil – see **Appendix 2**). The standardised spectral weighting functions are plotted in the third toolbox figure (also **Figure 5.1** above). The '**Chart input**' box allows the user to select one of these photoreceptor channels. The weighted power for this photoreceptor is then shown in the upper graph on the Toolbox application in red, compared against the unweighted irradiance incident on the surface of the eye in blue. As the chart input is changed in this section, the red line showing the weighted power will change depending on the λ_{max} of the chosen photopigment.

In addition, the α-opic lux values for each photopigment channel are shown in the second graph on the Toolbox application. Examples of these outputs are shown in **Figure 5.2**, along the bottom row.

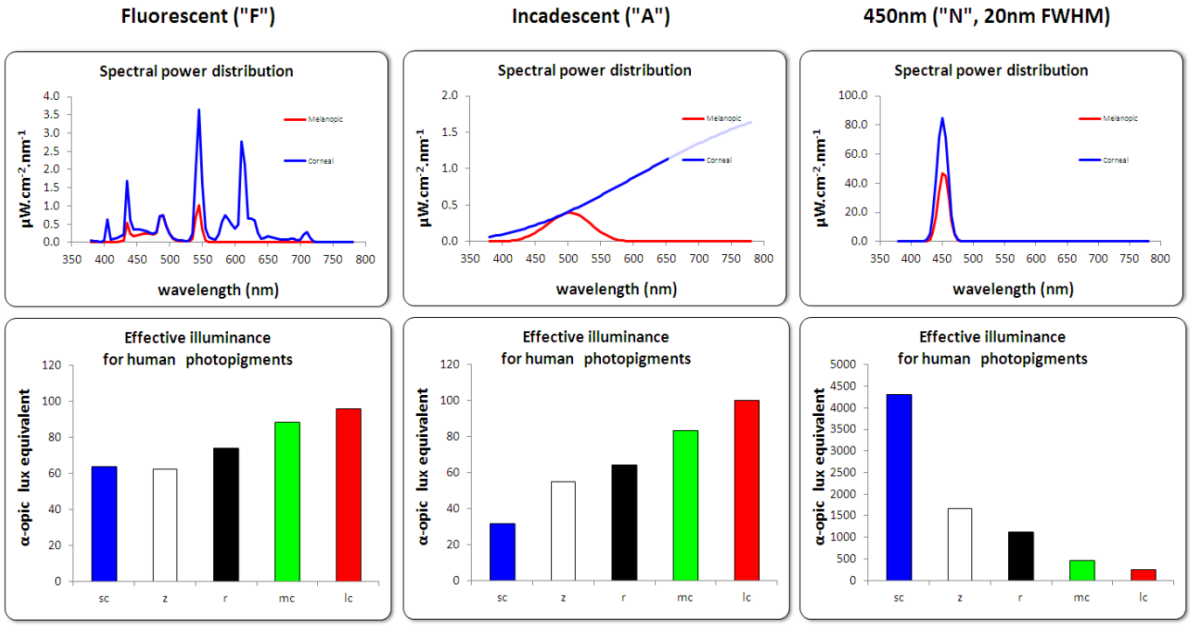

Figure 5.2. Examples of equivalent α-opic lux outputs. 100 photopic lux of three light sources (fluorescent, incandescent and 450 nm narrowband) are shown to compare their equivalent α-opic illuminance for the photopigment complement of the human retina. Upper panels show spectral power distribution (blue) with melanopic weighted power (red). Lower panels show lux equivalents for all 5 photoreceptors. 100 photopic lux of fluorescent light provides similar equivalent lux values for the chloropic and erythropic functions (mc and lc), as these photopigments have a similar peak sensitivity to the photopic sensitivity function V(λ). Lower levels, however, are apparent for rhodopic, melanopic and cyanopic functions (r, z and sc). For incandescent light, similar values are again obtained with much lower equivalent cyanopic lux (sc). For a narrowband 450 nm source (20 nm FWHM), 100 photopic lux produces a greatly enhanced equivalent cyanopic lux, with very low levels of rhodopic (r), chloropic (mc) and erythropic (lc) activation.

6. Unweighted summations from 380 to 780 nm inclusive (outputs)

Three types of unweighted, or radiometric, output quantities are provided here for the light source defined by the user (see **Sections 1-2**). This enables conversion between photometric and radiometric units. Once a light source is specified, the output quantities are given here in radiometric units:

i. $\mu W/cm^2$
ii. photons/cm^2/s
iii. log quanta = $\log_{10}$ photons/cm^2/s

For example, a standard fluorescent spectral power distribution (F), of 100 lux, will be equivalent to 29.7 $\mu W/cm^2$, 8.24E+13 photons/cm^2/s or 13.92 log quanta. (The remainder of this guide adopts

photons/cm^2/s and, for related log quanta, the notation aE+n for the more usual convention a * 10^n for consistency with Excel cell number formats, as well as using log to indicate $\log_{10}$.)

Note that radiation outside the range 380-780 nm is excluded (378-782 nm for 1 nm resolution data), so conversions including radiation outside this range are not supported.

7. Accuracy and limitations

The toolbox is based on data for ocular pre-receptoral transmittance quoted at 10 nm intervals (see **standard observer, Appendix 3**). In addition, **Appendix 3** lists the wavelength of maximum sensitivity for each photoreceptor template, which is based on a goodness of fit statistic that is relatively insensitive to small variations the peak wavelengths. For this reason, the toolbox is built to perform calculations using 5 nm wavelength bins (rather than 1 nm bins).

Idealised monochromatic sources cannot be specified at exact wavelengths in the toolbox. If equivalent α-opic lux calculations of this sort are required, the reference functions can be used for an interpolation. However, it is doubtful whether the increase in mathematical accuracy would be particularly useful. Inter-comparisons of calibrations traceable to primary standards between independent laboratories would probably be needed to convincingly demonstrate reproducible improvements in accuracy.

B) EXAMPLES OF USE

Example 1 – Use of user-measured SPD ('5nm')

In a study on a non-visual response to light in healthy human subjects such as circadian phase-shifting, a white LED light source was used. The spectral power distribution incident on the surface of the eye was measured with a suitably calibrated spectroradiometer.

1. Select '5nm spectral data' mode.
2. Enter the spectral power distribution between 380-780 nm in column AH. This can be obtained by making a measurement with a calibrated spectrophotometer. The SPD used in this example is shown in **Figure B1** and the measured SPD is provided in **Appendix 4** as **Table A4.1**. No more inputs are required in this mode.
3. The equivalent α-opic lux values for this white LED light are:
    i. Cyanopic lux 516.41
    ii. Melanopic lux 528.50
    iii. Rhodopic lux 488.95
    iv. Chloropic lux 444.85
    v. Erythropic lux 406.19

These values are summarised in **Figure B1**. This LED provides a greater proportion of melanopic light, similar to the daylight standard D_{65}.

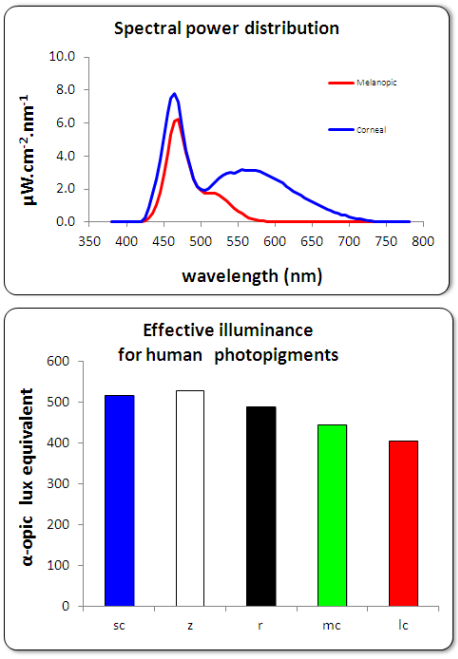

Figure B1. 406 lux of a user-measured white LED light provides comparable equivalent α-opic lux values for all 5 functions. Higher melanopic (z) and rhodopic (r) values are obtained than for cyanopic (sc) and chloropic (mc), with lowest levels of erythropic lux (lc).

The data in **Appendix 4** has a similar SPD as Light source option 'L', with irradiance 145.90µW/cm^2 but a higher CCT of around 9270 K.

The 1nm spectral data option works in the same way, so no separate example is provided. Notice how the upper chart appears when you change the mode to 1nm spectral data. When switching between 1nm and 5nm modes, the SPD in column AH must be changed to the correct resolution.

Example 2 - Comparison of white light sources ('Approximate')

Two further studies evaluated the same circadian response to light in human subjects. The first used 1000 lux of incandescent light, the second 1000 lux of fluorescent light. How comparable are these studies?

Answer: We don't know. If it is reasonable, however, to presume the light sources correspond to options 'A' and 'F' closely CIE standard illuminants A and F11 respectively), we can use the model to make an estimate:

1. Select 'approximate mode'.
2. Select 'A' for light source (incandescent), 'L' for units and enter 1000 for 'Amount'
    a. For the second column below, simply switch to 'F' for light source (fluorescent)
3. Unweighted output values are given as follows:

		'A', incandescent	'F', fluorescent
i.	Power, $\mu W/cm^2$	648.76	297.03
ii.	$Photons/cm^2/s$	2.13E+15	8.24E+14
iii.	Log Quanta	15.33	14.92

4. Equivalent α-opic lux values are as follows:

		'A', incandescent	'F', fluorescent
i.	Cyanopic lux	315.89	635.21
ii.	Melanopic lux	547. 28	621.55
iii.	Rhodopic lux	642.81	739.02
iv.	Chloropic lux	835.17	887.05
v.	Erythropic lux	1001.64	961.51

This is summarised in **Figure B2**.

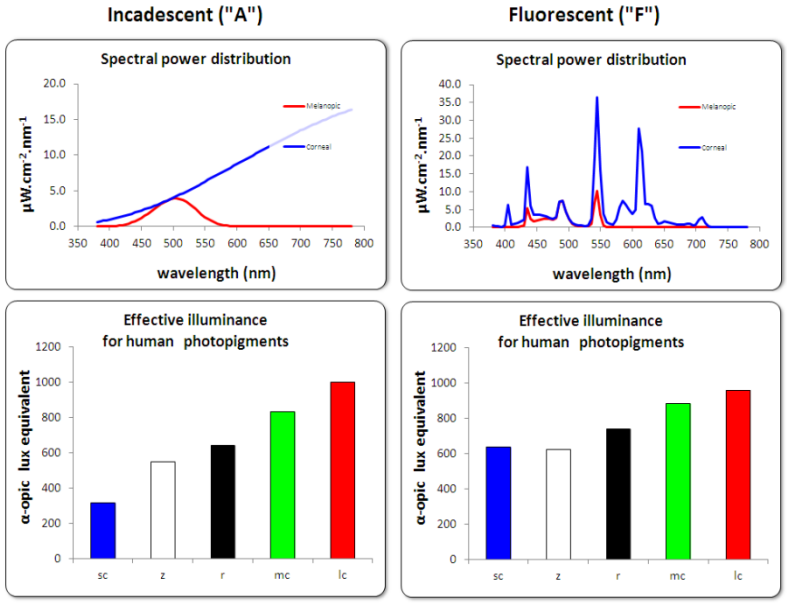

Figure B2. Comparison of 1000 lux of incandescent and fluorescent light. Whilst there is little difference in the equivalent α-opic lux values at longer wavelength (lc, mc and r), for the melanopic function (z) there is a difference of around 75 equivalent melanopic lux (14% more), and for the cyanopic function (sc) the fluorescent light provides around 320 more equivalent cyanopic lux than incandescent light (more than double). Therefore data from a study using fluorescent light would be expected to have an increased stimulation of blue cone and melanopsin pigments.

Example 3 – Simple light conversion
A light source passed through a glass monochromatic interference filter is reported to provide 14.5 log quanta of 480 nm narrowband light with a 10 nm FWHM. What is the total output in µW/cm^2?

1. In 'approximate mode', select 'N' for narrowband under 'Light Source'
2. Select 'Q' for 'Units' in log quanta
3. Enter 14.5 log quanta in section 2 under 'Amount' (14.5 log quanta = 3.16E+14 photons/cm^2/s).
4. In section 3, enter 480 for 'Narrowband peak' to specify peak wavelength in nm and enter 10 nm for 'Narrowband FWHM'.
5. Output values are given in section 6 and should read:
    i. Power, µW/cm^2 130.87
    ii. Photons/cm^2/s 3.16E+14
    iii. Log quanta 14.50

This light source therefore provides 130.87 µW/cm^2 in the plane of measurement at that point.

Full and reduced spectral output forms are shown below in **Figure B3**.

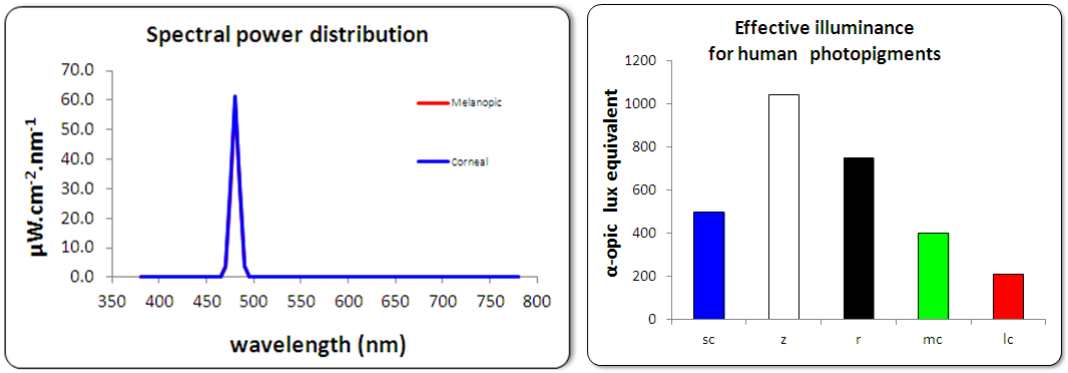

Figure B3. Spectral power distribution and human retinal photopigment sensitivity of a 14.5 log quanta 480 nm narrowband light source, FWHM = 10 nm. Such a stimulus would clearly activate the melanopic photoreceptor channel (z), but would also produce significant rhodopic activation. Note that the red line is obscured by the blue line, as the melanopic sensitivity function is close to maximal between 450 and 500 nm.

This can be confirmed with simple manual calculations (ignoring spectral distributions):

Radiometric irradiance ≈ 3.16E+14 * 6.6E-34 * 3e+8 / 480E-9 * 1E+6 = 130.35 µW/cm^2
The toolbox calculation gives 130.87 µW/cm^2, which is in close agreement with this rough estimate.

- In the above estimate 6.6E-34 * 3e+8 / 480E-9 = hc/λ converts from quanta/s to W and the factor 1e+6 converts from W/cm^2 to µW/cm^2.

Photopic illuminance ≈ 130.35 * V(480 nm) * 683 * 1E-6 * 1E+4 = 124.64 lux (as V(480 nm) ≈ 14%).
The toolbox calculation gives 125.67 lux, which is in close agreement with this rough estimate.

- 1E-6 * 1E+4 converts from µW/cm^2 to W/m^2 and V(λ) * 683 converts from W/m^2 to lux.

APPENDIX 1 – EQUIVALENT α-OPIC ILLUMINANCE

Each *equivalent α-opic illuminance* (symbol E_α; unit: α-opic + lux, lx, lumen per square metre, lm.m^{-2}) specifies a photometric quantity related to the spectral power distribution of irradiance $E_{e,\lambda}(\lambda)$ by the following equation. The absolute sensitivity is identical to photopic illuminance for light with an equal-energy spectral power distribution.

$$E_\alpha = K_m \int E_{e,\lambda}(\lambda)\, N_\alpha(\lambda)\, d\lambda \cdot \int V(\lambda)\, d\lambda \,/\, \int N_\alpha(\lambda)\, d\lambda \qquad \text{(A1.1), where}$$

- λ is the wavelength of the radiation
- $K_m = 683.002\ \mathrm{lm/W}$, the maximum spectral *luminous efficacy**
- $V(\lambda)$ is the *spectral luminous efficacy** function for photopic vision
- $E_{e,\lambda}(\lambda)$ is the spectral power distribution
- $N_\alpha(\lambda)$ is the α-opic sensitivity curve ***with arbitrary normalisation***.

α specifies the retinal photopigment for a given organism. For example, the five human variants are:

cyanopic, relating to the s-cone photopigment
chloropic, relating to the m-cone photopigment
erythropic, relating to the l-cone photopigment
rhodopic, relating to rhodopsin
melanopic, relating to melanopsin

As $\int V(\lambda)\, d\lambda = 106.857$ and choosing to define $\int N_\alpha(\lambda)\, d\lambda = 1$, equation A1.1 can be simplified to an equivalent form to that calculations for photopic lux:

$$E_\alpha = 72\,983.25 \int E_{e,\lambda}(\lambda)\, N_\alpha(\lambda)\, d\lambda \qquad \text{(A1.2)}$$

The spectral sensitivity curves $N_\alpha(\lambda)$ for each of the human photopigments are provided in the worksheet labelled 'Reference' and can be used to calculate E_α using either equations A1.1 or A1.2.

* For definitions of these terms see the CIE's International Lighting Vocabulary at eilv.cie.co.at

Previous definitions

To avoid confusion with 'melanopic illuminance' previously provided [S7], the terminology 'equivalent α-opic illuminance' should be used. The spectral efficiency function $N_z(\lambda)$ proposed here is essentially proportional to the $V_z(\lambda)$ of al Enezi et al (2011), however its scaling is different. This has the effect of allowing the newly proposed equivalent melanopic illuminance to be equal to photopic lux, and all other equivalent α-opic illuminances, for an equal-energy radiator. As the current method also provides smaller and more manageable values under most circumstances we propose that it replaces that outlined in al Enezi et al (2011). Melanopic lux calculated according to the prescription given by Enezi et al (2011) can be converted into **equivalent** melanopic lux, simply by multiplying by 1 / 5.4.

At present there is no adopted international standard; our proposals here originate from suggestions made at the 1st International Workshop on Circadian Neurophysiological Photometry held in Didsbury, Manchester, UK on 10-12 January 2013.

APPENDIX 2 – PRE-RECEPTORAL FILTERING

A modified version of the Pokorny and Smith (1997) [S8] lens density function has been used to estimate pre-receptoral filtering based on age and undilated pupil state (Price LLA and Peirson, SN unpublished analysis). The effects of luteal/macular pigment are not included as non-image-forming responses are assumed to originate predominantly outside of the central retina [S9]. This is shown in **Table A2.1** and plotted in **Figure A2.1**. These values are also provided in the worksheet labelled 'Reference' at 5 nm intervals.

Wavelength (nm)	Transmittance
380	0%
390	1%
400	3%
410	8%
420	18%
430	26%
440	33%
450	38%
460	42%
470	46%
480	49%
490	52%
500	54%
510	57%
520	58%
530	60%
540	62%
550	64%
560	66%
570	68%
580	69%
590	71%
600	72%
610	73%
620	74%
630	74%
640	75%
650	76%
660	76%
670	77%
680	77%
690	77%
700	78%
710	78%
720	78%
730	78%
740	78%
750	79%
760	79%
770	79%
780	79%

Table A2.1. Transmittance values based on a 32 year old standard observer used for lux-equivalent values.

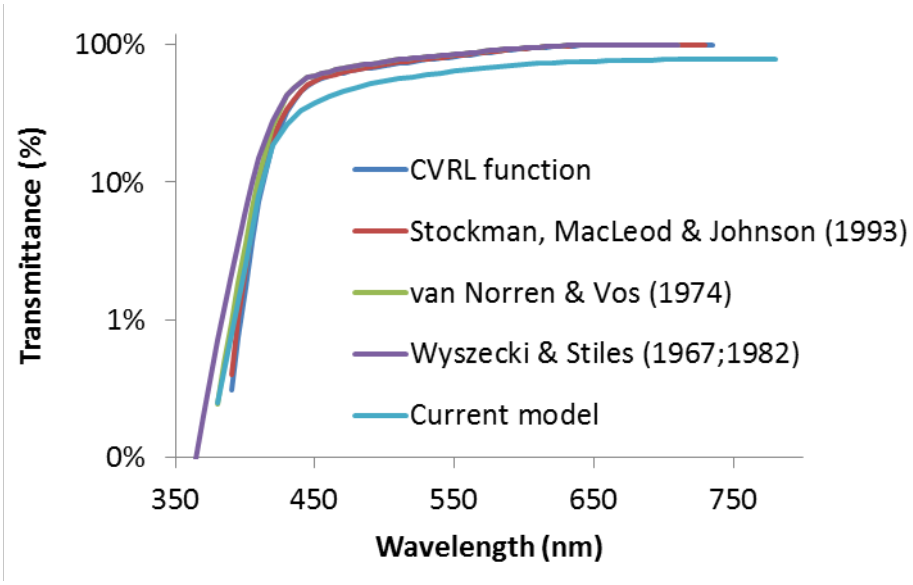

Figure A2.1. Comparison of the toolbox model (Price LLA and Peirson, SN unpublished analysis) for standard observer against existing lens transmission models [S10-S14]. The model used herein is broadly comparable across most wavelengths, but does not approach 100% transmission at longer wavelength for consistency with empirically measured lens data.

APPENDIX 3 - TERMINOLOGY

Chloropic. Relating to human green cone photopigment absorption. Chloropic lux is weighted to a photopigment with λ_{max} 534 nm with pre-receptoral filtering based on a 32 year old standard observer. Chloropic lux is written in full as equivalent chloropic lux and the peak sensitivity is based radiation incident at the retina; this also applies to each of the five lux values mentioned in this appendix (see Standard Observer).

Cyanopic. Relating to human blue cone photopigment absorption. Cyanopic lux is weighted to a photopigment with λ_{max} 420 nm with pre-receptoral filtering based on a 32 year old standard observer.

Erythropic. Relating to human red cone photopigment absorption. Erythropic lux is weighted to a photopigment with λ_{max} 564 nm with pre-receptoral filtering based on a 32 year old standard observer.

FWHM. Full-width half maximum. The wavelength range of the spectral power distribution for a narrowband light source, based on the width of the SPD at half maximum.

Melanopic. Relating to human melanopsin photopigment absorption. Melanopic lux is weighted to a photopigment with λ_{max} 480 nm with pre-receptoral filtering based on a 32 year old standard observer (see Appendix 1 for comments about previous definitions).

Rhodopic. Relating to rod photopigment absorption. Rhodopic lux is weighted to λ_{max} 498 nm with pre-receptoral filtering based on a 32 year old standard observer.

SPD. Spectral Power Distribution. For most calculations SPDs are considered as relative spectral power distributions (RSPD), that is, normalised so that the total power = 100%.

Standard observer. When defining standard measures, pre-receptoral filtering is based on that from a 32-year old. This is based on lens values from Pokorny and Smith (1997) [S8], Wyszecki and Stiles (1967; 1982) [S13-14] using the average age from Stiles and Burch (1955, 1959) [S15-16], being similar to the ages of the studies which informed the lux in Gibson and Tyndall (1923) [S17]. For the calculation of equivalent lux values, a dilated pupil (>7mm) is assumed.

APPENDIX 4 – SAMPLE SPECTRAL POWER DISTRIBUTION

A sample white light LED spectral power distribution is provided below as a 'user-measured' SPD

nm	µW/cm^2
380	0.0000
385	0.0000
390	0.0000
395	0.0000
400	0.0000
405	0.0000
410	0.0000
415	0.0000
420	0.0000
425	0.2799
430	0.8876
435	1.7512
440	2.5931
445	3.7628
450	5.1954
455	6.6186
460	7.5093
465	7.7596
470	7.2658
475	5.7131
480	4.3449
485	3.4551
490	2.6055
495	2.1620
500	1.9609
505	1.9174
510	2.0548
515	2.2236
520	2.4649
525	2.6825
530	2.8380
535	2.9276
540	2.9996
545	2.9669
550	3.0781
555	3.1630
560	3.1342
565	3.1400
570	3.1209
575	3.1232
580	3.0818

585	2.9267
590	2.8229
595	2.7252
600	2.6054
605	2.4744
610	2.3689
615	2.1703
620	2.0266
625	1.8683
630	1.7604
635	1.6256
640	1.4568
645	1.3488
650	1.2303
655	1.1009
660	0.9818
665	0.8947
670	0.7771
675	0.6953
680	0.6172
685	0.5137
690	0.4412
695	0.4271
700	0.3095
705	0.2595
710	0.2105
715	0.1684
720	0.1237
725	0.0911
730	0.0693
735	0.0308
740	0.0000
745	0.0000
750	0.0000
755	0.0000
760	0.0000
765	0.0000
770	0.0000
775	0.0000
780	0.0000

Table A4.1. The spectral power distribution of the cool white LED (CCT ≈ 9500 K) for **Example B1**.

REFERENCES

[S1] CIE (2012). CIE S 017/E:2011 ILV: International Lighting Vocabulary. Vienna: Commission Internationale de l'Eclairage; 2012. eilv.cie.co.at

[S2] Dartnall HJ, Bowmaker JK, Mollon JD (1983). Proc R Soc Lond B. Nov 22;220(1218):115-30.

[S3] Govardovskii VI, Fyhrquist N, Reuter T, Kuzmin DG, Donner K (2000). In search of the visual pigment template. Vis Neurosci. Jul-Aug;17(4):509-528.

[S4] Lamb, TD (1995). Photoreceptor spectral sensitivities: common shape in the long-wavelength region. Vision Research. 35 (22), 3083-3091.

[S5] Stockman, A & Sharpe, LT (2000). The spectral sensitivities of the middle- and long-wavelength-sensitive cones derived from measurements in observers of known genotype. Vision Res. 40 (13), 1711–1737.

[S6] Stockman, A, Sharpe, LT & Fach, C (1999). The spectral sensitivity of the human short-wavelength sensitive cones derived from thresholds and color matches. Vision Res. 39 (17), 2901–2927.

[S7] Al Enezi J, Revell V, Brown T, Wynne J, Schlangen L and Lucas R (2011). A "melanopic" spectral efficiency function predicts the sensitivity of melanopsin photoreceptors to polychromatic lights. J Biol Rhythms.; 26(4):314-323.

[S8] Pokorny J and Smith, VC (1997). The Verriest Lecture. How much light reaches the retina? In C.R. Cavonius (ed), Colour Vision Deficiencies XIII. Documenta Ophthalmologica Proceedings Series 59:491-511.

[S9] Dacey DM, Liao HW, Peterson BB, Robinson FR, Smith VC, Pokorny J, Yau KW and Gamlin PD (2005). Melanopsin-expressing ganglion cells in primate retina signal colour and irradiance and project to the LGN. Nature. 433(7027):749-754.

[S10] CVRL. Colour and Vision Research Laboratory. www.cvrl.org

[S11] Stockman A, MacLeod DIA & Johnson NE (1993). Spectral sensitivities of the middle- and long-wavelength sensitive cones. Journal of the Optical Society A, 10, 2491-2521.

[S12] van Norren, D & Vos JJ (1974) Spectral transmission of the human ocular media Vision Research, 14, 1237-1244.

[S13] Wyszecki G & Stiles WS (1967). Color Science New York: Wiley.

[S14] Wyszecki G & Stiles WS (1982). Color Science (2nd ed.). New York: Wiley.

[S15] Stiles WS & Burch JM (1955). Interim report to the Commission Internationale de l'Éclairage Zurich, 1955, on the National Physical Laboratory's investigation of colour-matching (1955) with an appendix by W. S. Stiles & J. M. Burch. Optica Acta, 2, 168-181.

[S16] Stiles WS & Burch JM (1959). NPL colour-matching investigation: Final report. Optica Acta, 6, 1-26.

[S17] Gibson KS and Tyndall EPT (1923). The Visibility of Radiant Energy, Sci. Pap. Bur. Stand. 19, 131-191.