



# Human Centric Lighting

Daylight-Related Metrics  
as prerequisite for assessment of light quality  
and for lighting design

# Light Affects Humans

## Light is Vision

Brightness  
Information  
Shape, Color  
Images  
Constrast  
Perception



## Light is Biology

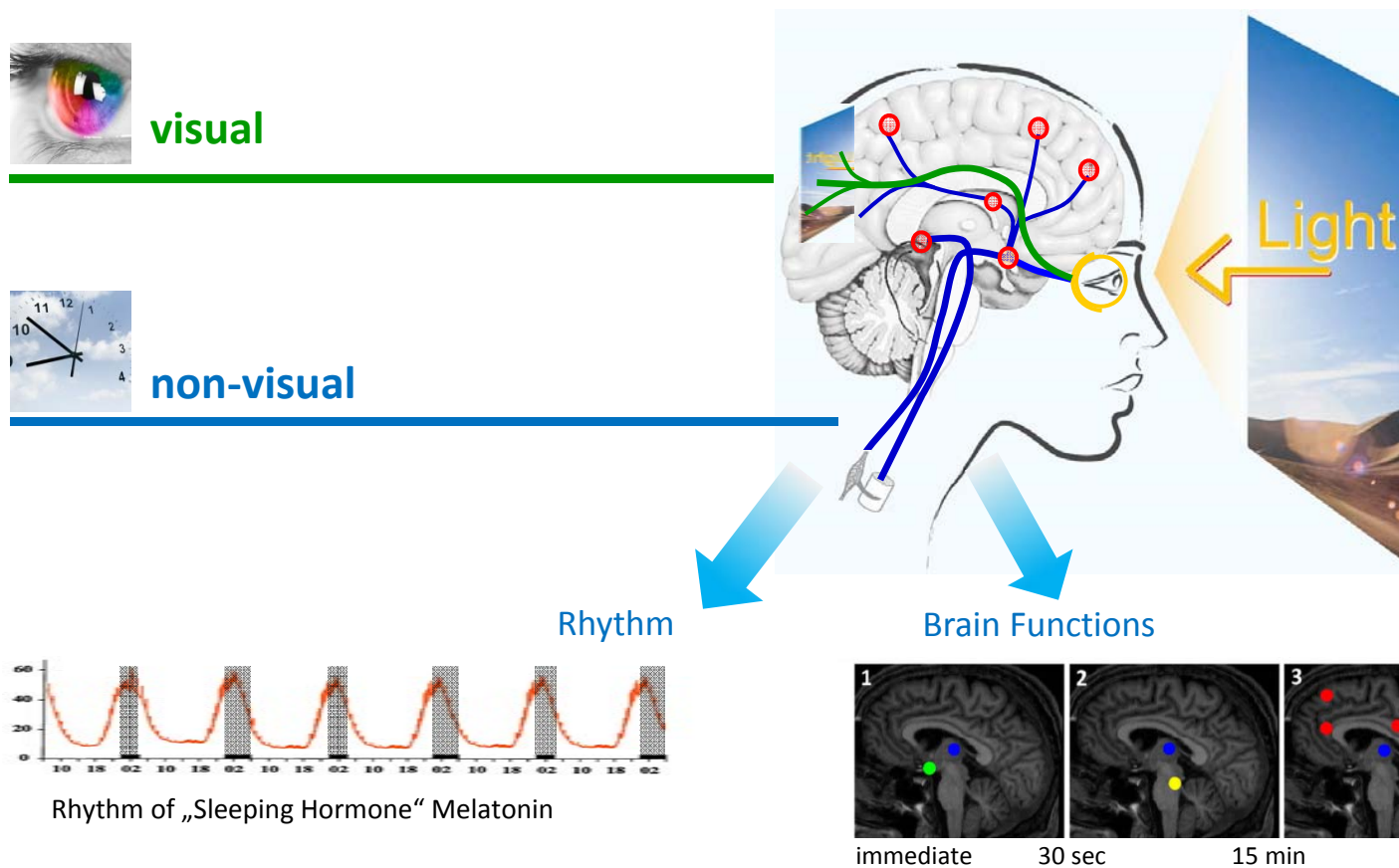
### Beyond Vision

Attention  
Hormones  
Alertness  
Circadian Rhythm  
Inner Clock  
Fatigue



# Human Centric Lighting

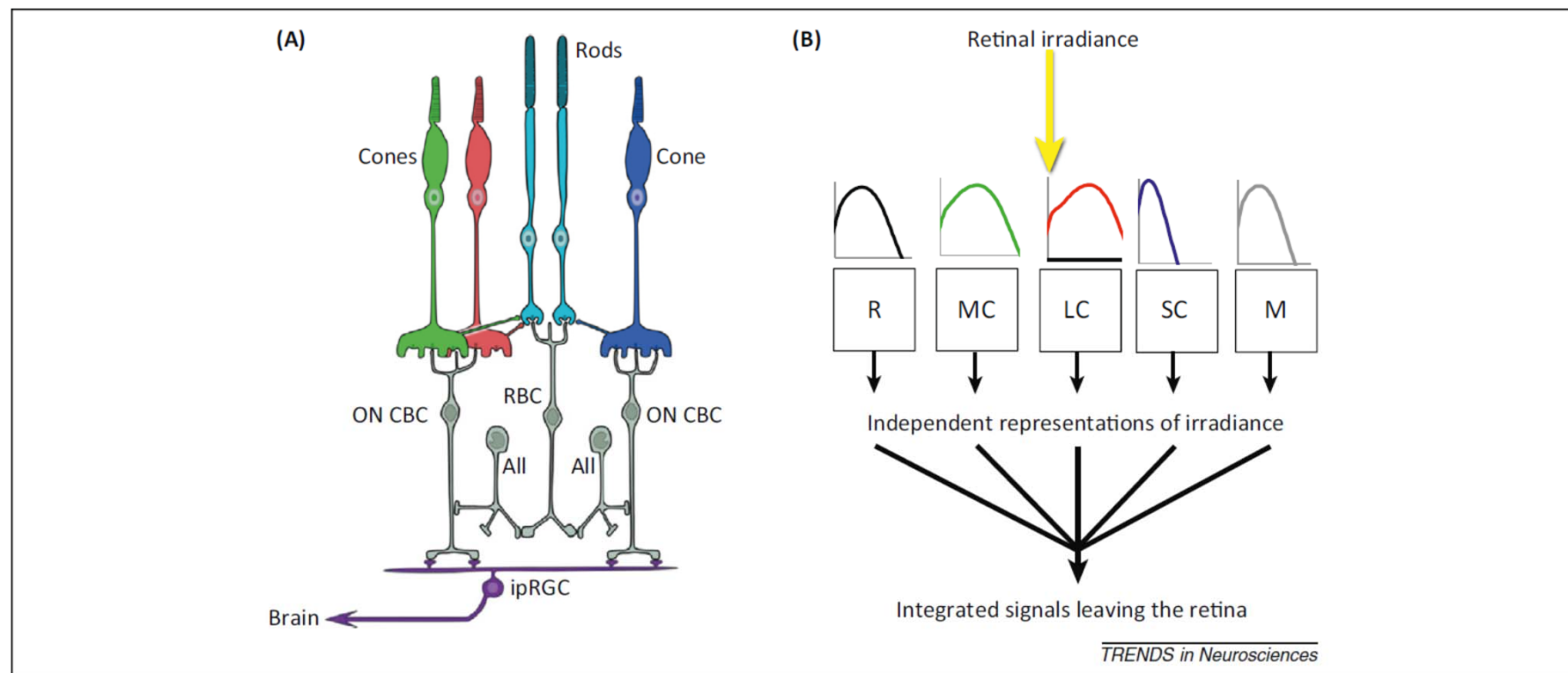
## Pathways of the Light in the Brain



Vandewalle &  
Dijk 2009

# Breakthrough-Publication in 2014

## Definition of photoreceptor sensitivity functions for five receptors



Trends in Neuroscience Jan. 2014, Vol. 37. No. 1

# Trends in Neuroscience Jan. 2014, Vol. 37. No. 1

## Measuring and using light in the melanopsin age

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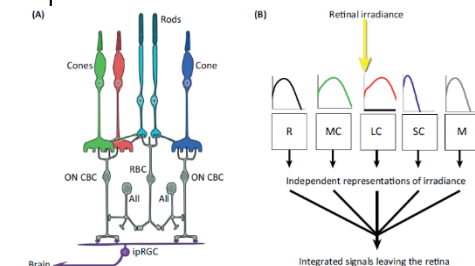
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<sup>9</sup> Department of Biology, University of Virginia, Charlottesville, VA, USA

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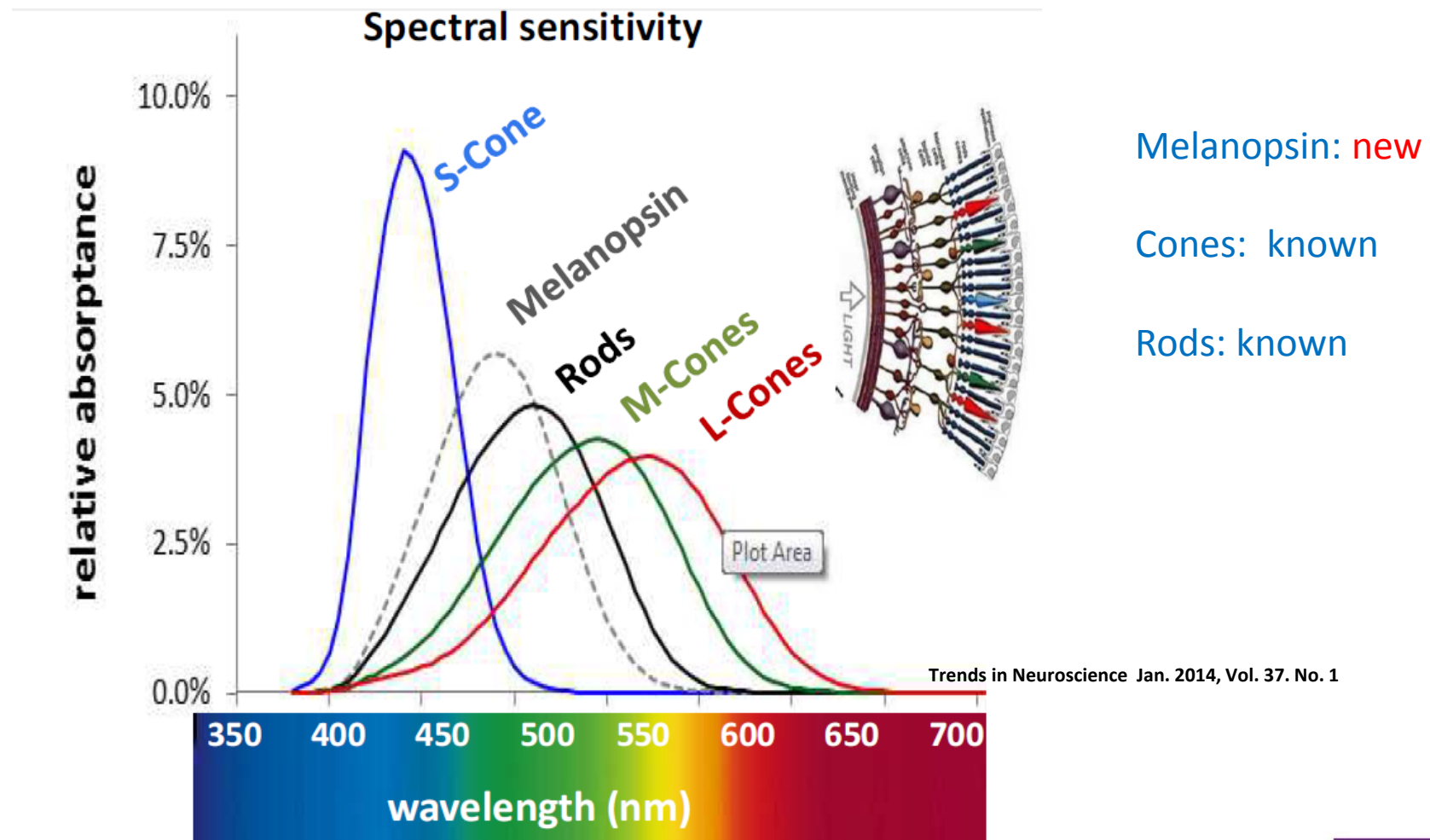
<sup>11</sup> Department of Neurology, Thomas Jefferson University, Philadelphia, PA, USA



Light is a potent stimulus for regulating circadian, hormonal, and behavioral systems. In addition, light therapy is effective for certain affective disorders, sleep problems, and circadian rhythm disruption. These biological and behavioral effects of light are influenced by a distinct photoreceptor in the eye, melanopsin-containing intrinsically photosensitive retinal ganglion cells (ipRGCs), in addition to conventional rods and cones. We summarize the neurophysiology of this newly described sensory pathway and consider implications for the measurement, production, and application of light. A new light-measurement strategy taking account of the complex photoreceptive inputs to these non-visual responses is proposed for use by researchers, and simple suggestions for artificial/architectural lighting are provided for regulatory authorities, lighting manufacturers, designers, and engineers.

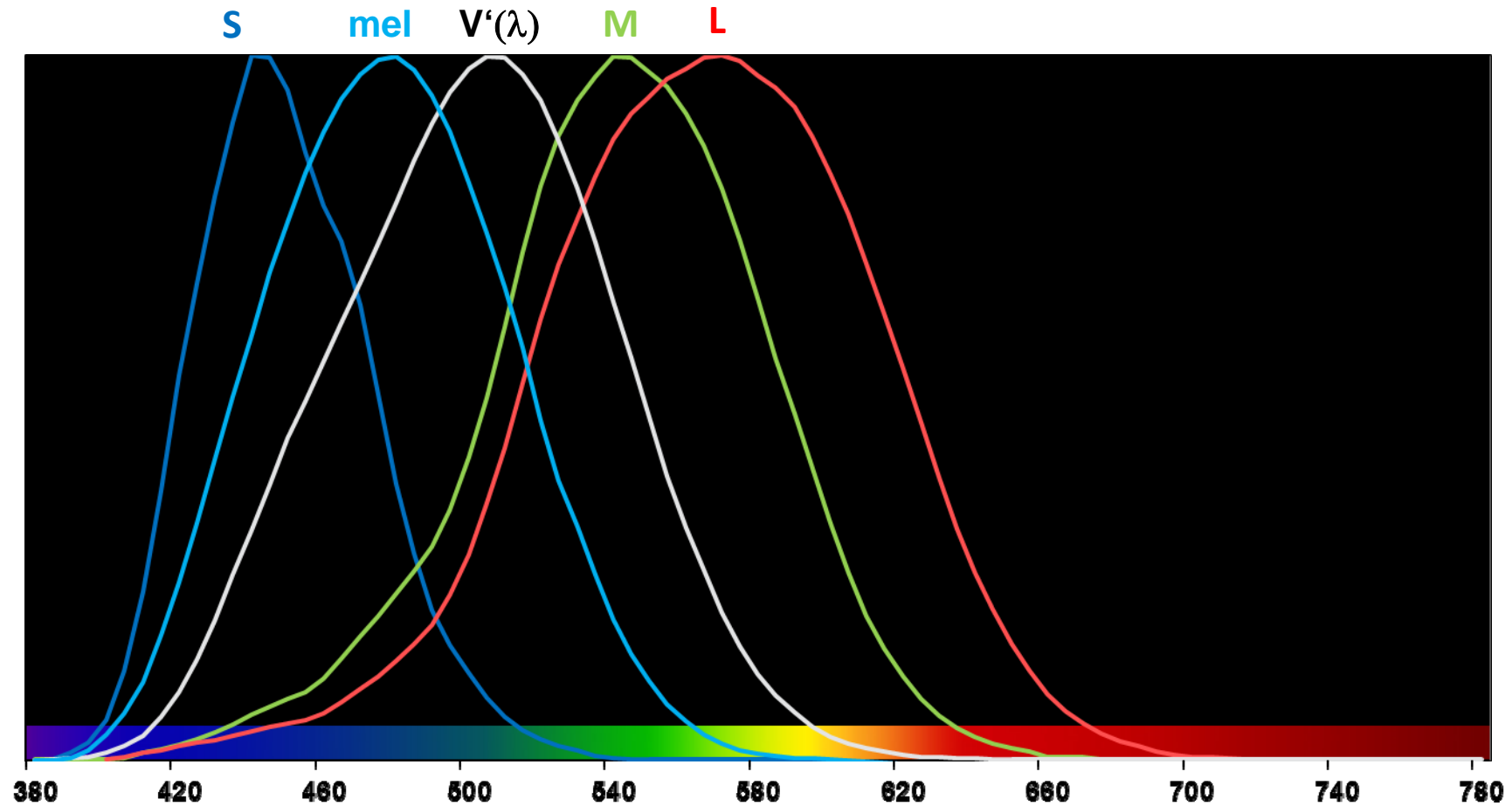
New approach by a scientific agreement on action spectra for non-visual effects of light on humans

# Biological Effects are Mediated by Five Photoreceptors



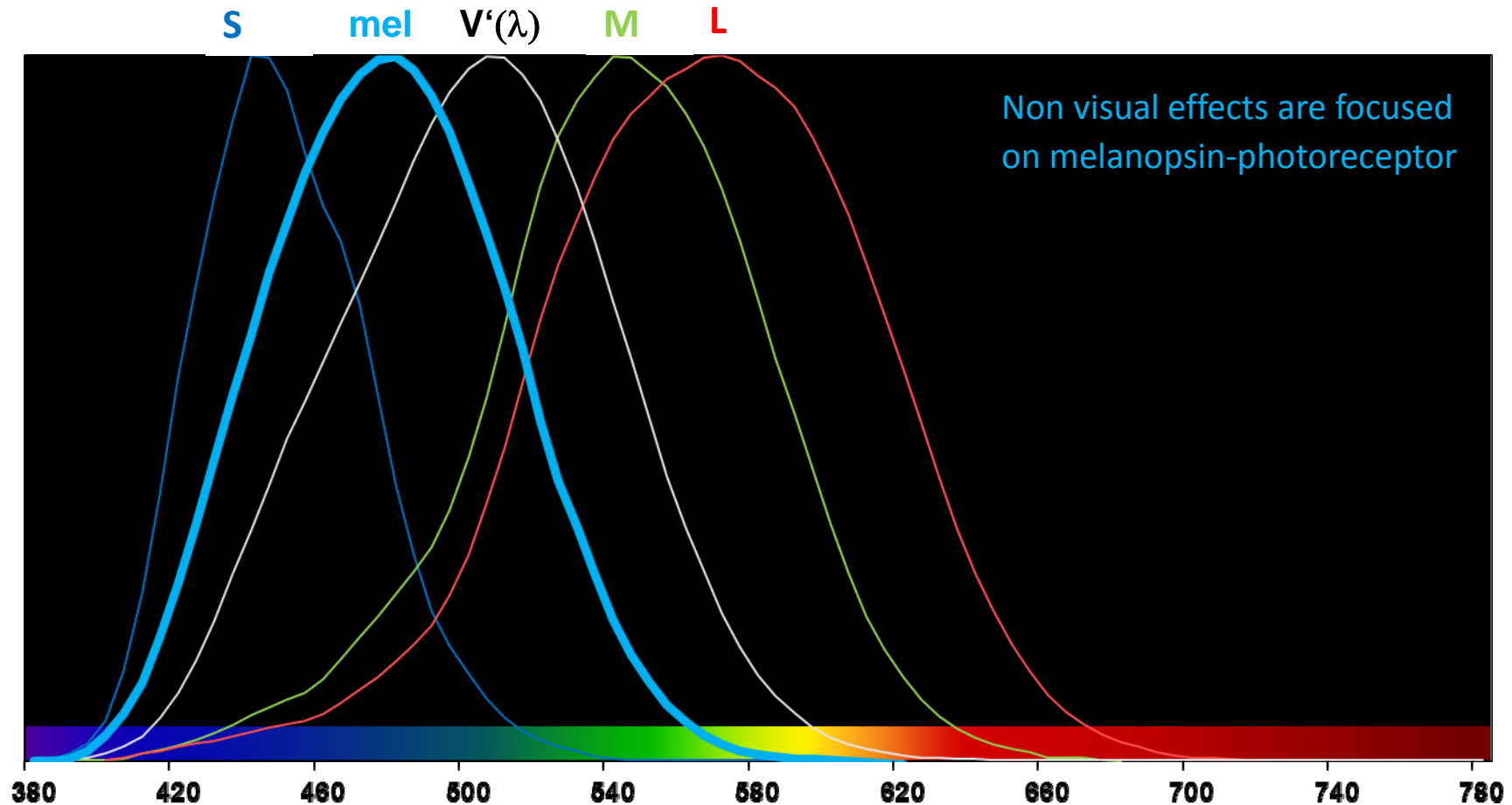


# Action Spectra of Retinal Photoreceptors



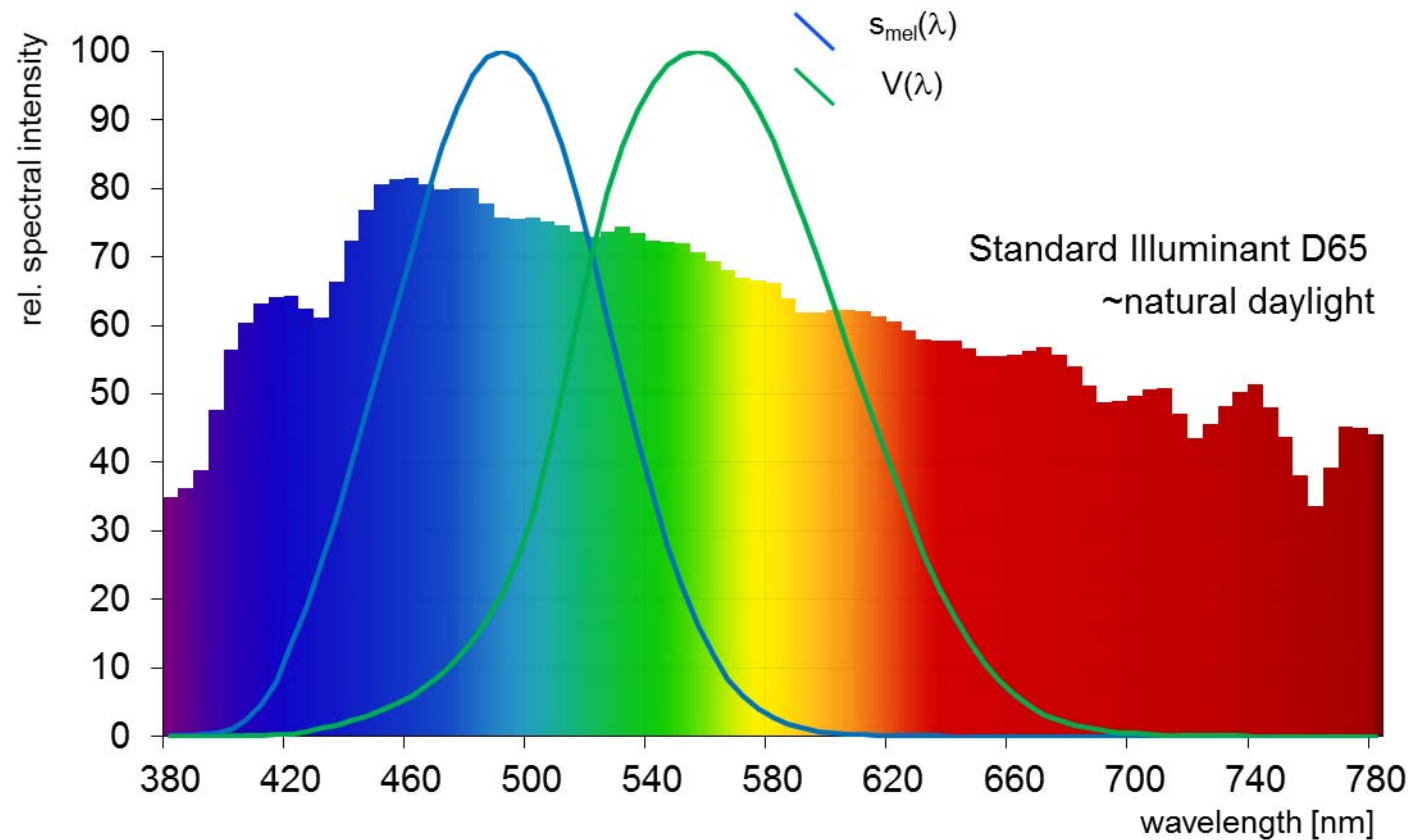
Action spectra normalized to maximum of 1 (as usual in photometry)

# Action Spectra of Retinal Photoreceptors



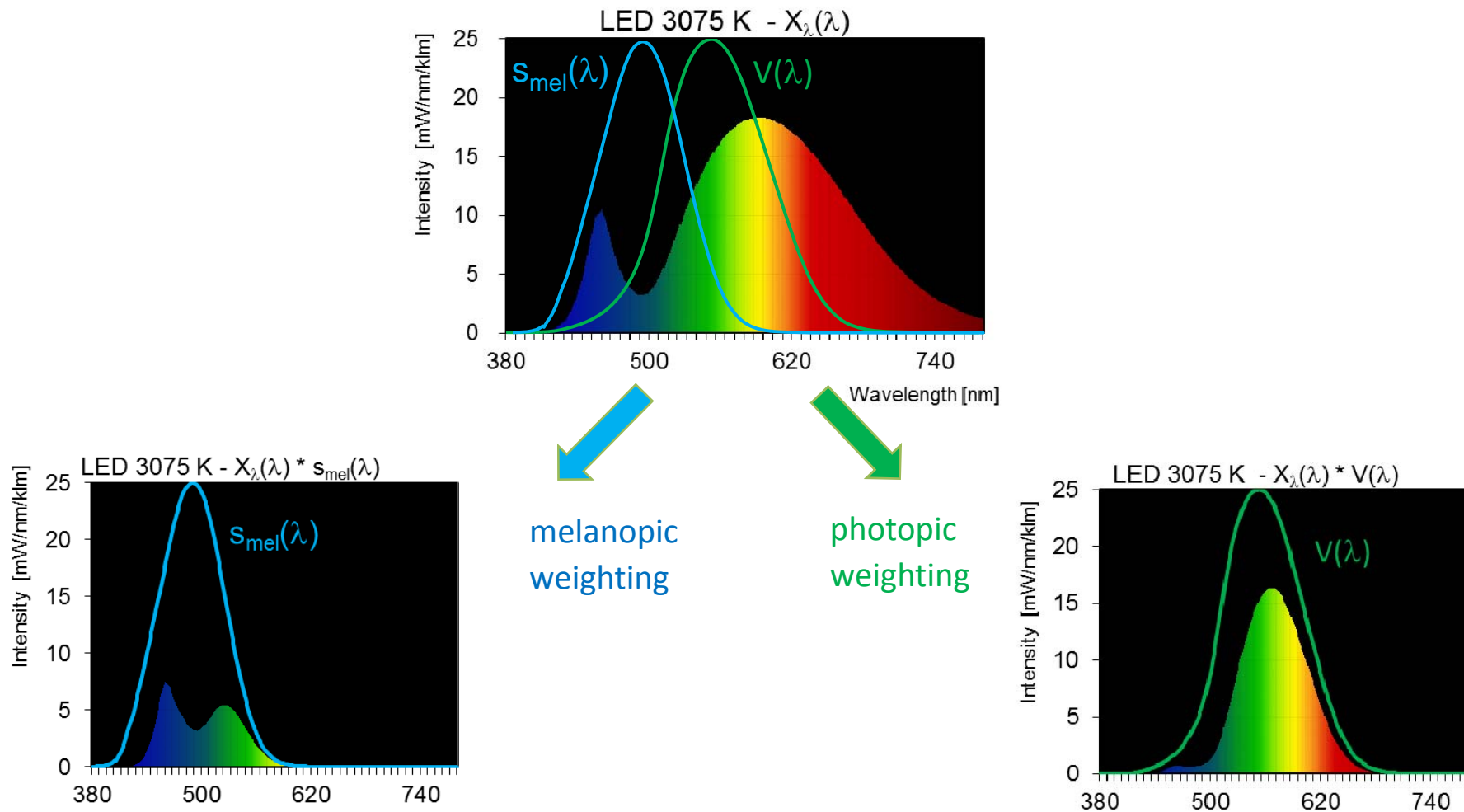


# Action Spectrum for Melanopsin Sensitivity (2014)



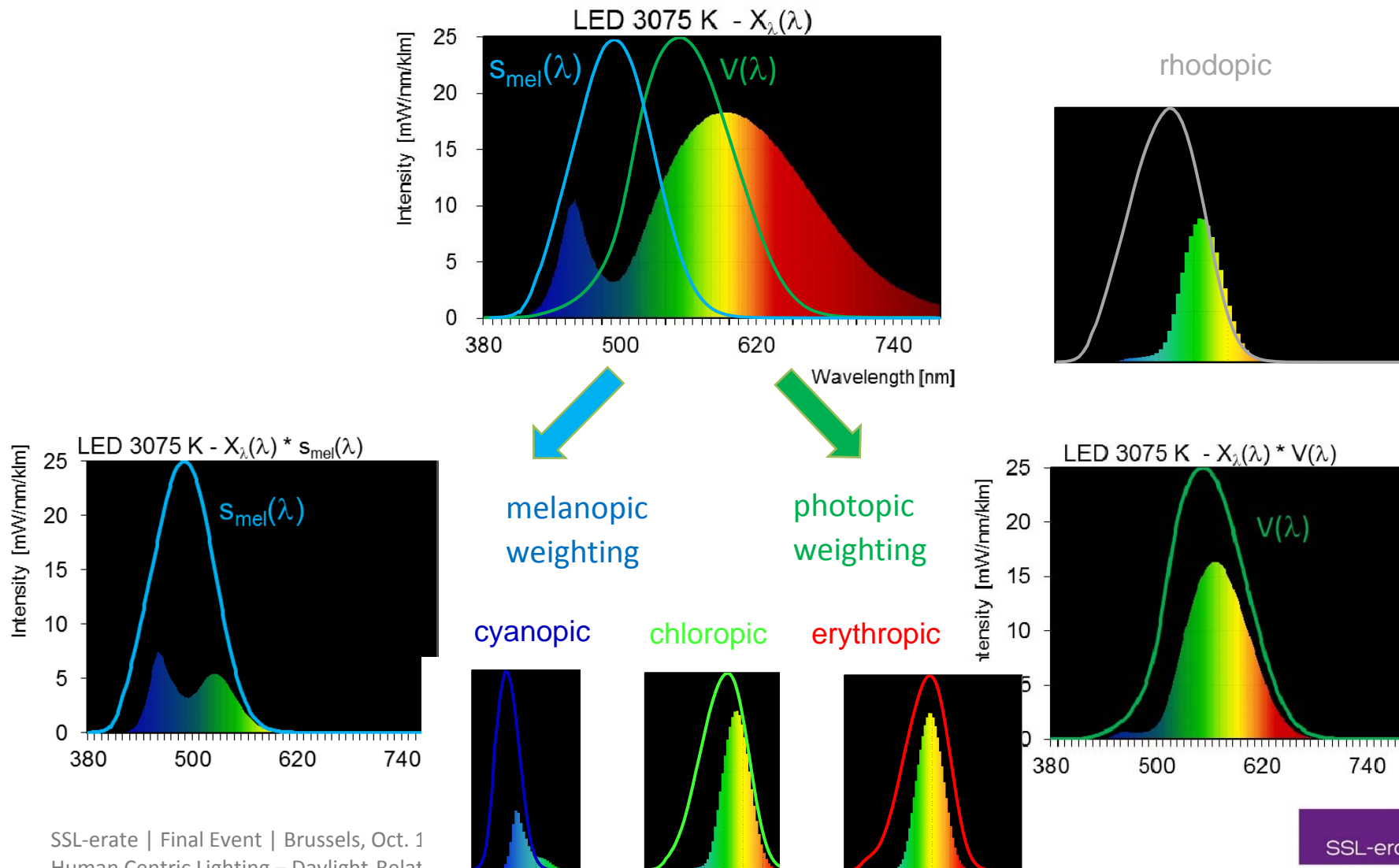
# Spectral Weighting Functions

- Melanopic and photopic weighted spectral power distribution



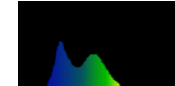
# Spectral Weighting Functions

- Melanopic and photopic weighted spectral power distribution



# Melanopic Irradiance

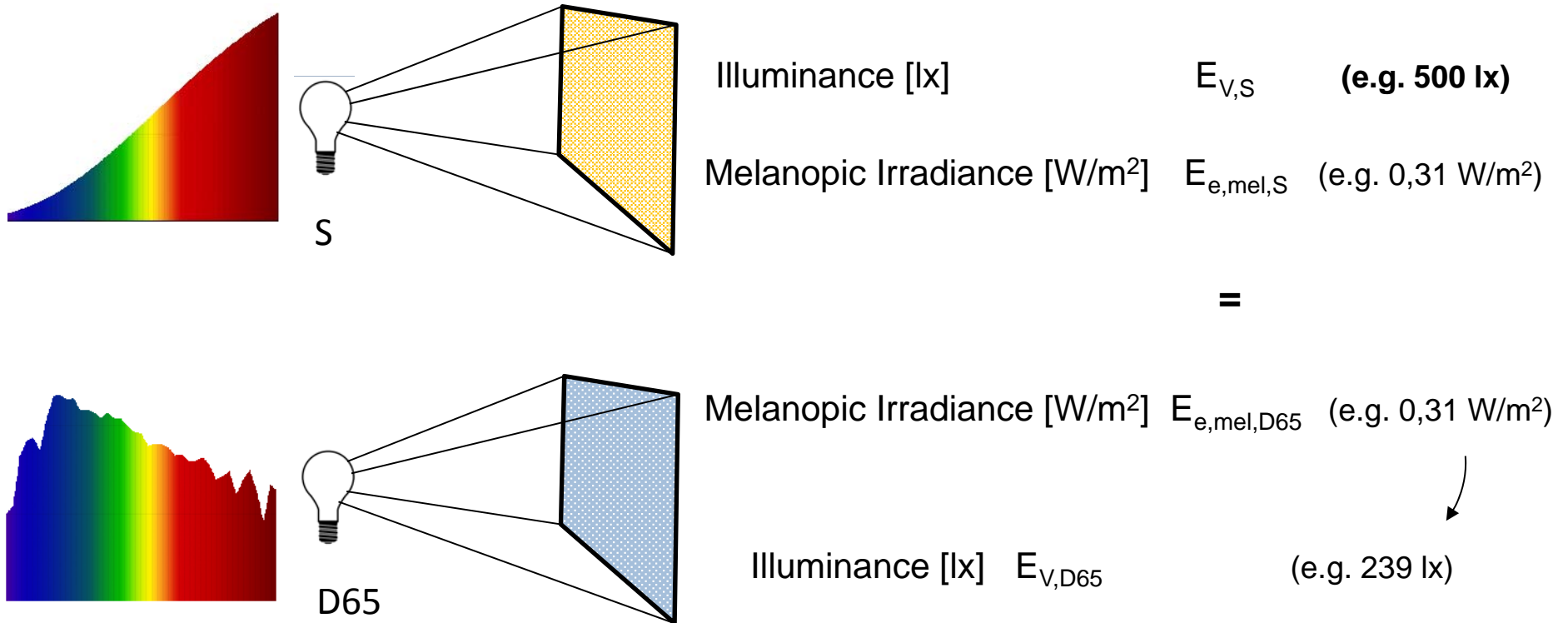
*melanopic irradiance = integral of the melanopic weighted spectral irradiance*



Illuminant	Melanopic irradiance $X_{e, mel}$ [ $W/m^2$ ] at 1000 lx
Std. illuminant A (CCT= 2856 K)	0,657
Fluorescent type CIE F10 (FL, CCT= 5000 K)	0,906
Fluorescent type CIE F12 (FL, CCT= 3000 K)	0,536
<b>Std. illuminant D65 (daylight CCT= 6500 K)</b>	<b>1,327</b>
illuminant P (candle light)	0,354
LED, white (CCT= 3075 K)	0,567
LED, white (CCT= 5400 K)	1,044
LED, white (CCT= 6535 K)	1,061
High CCT Fluorescent (CCT= 8000 K)	1,269

Melanopic efficacy of luminous radiation [mW/lm]
0,657
0,906
0,536
1,327
0,354
0,567
1,044
1,061
1,269

# Melanopic Daylight Equivalent Illuminance

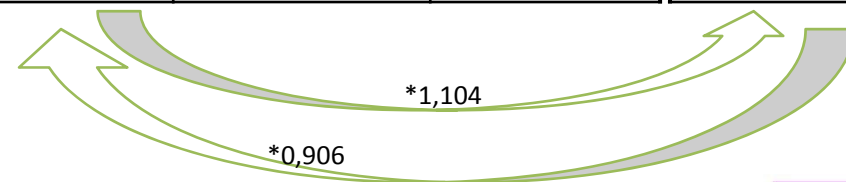


Melanopic Daylight Equivalent Illuminance [lx]  $E_{V,mel,D65,S}$  (e.g. 239 lx)

# Melanopic photometric data

- Examples for melanopic daylight equivalent illuminance  $E_{v, mel, D65}$
- Based on a (photopic) illuminance  $E_v$  of 1000 lx

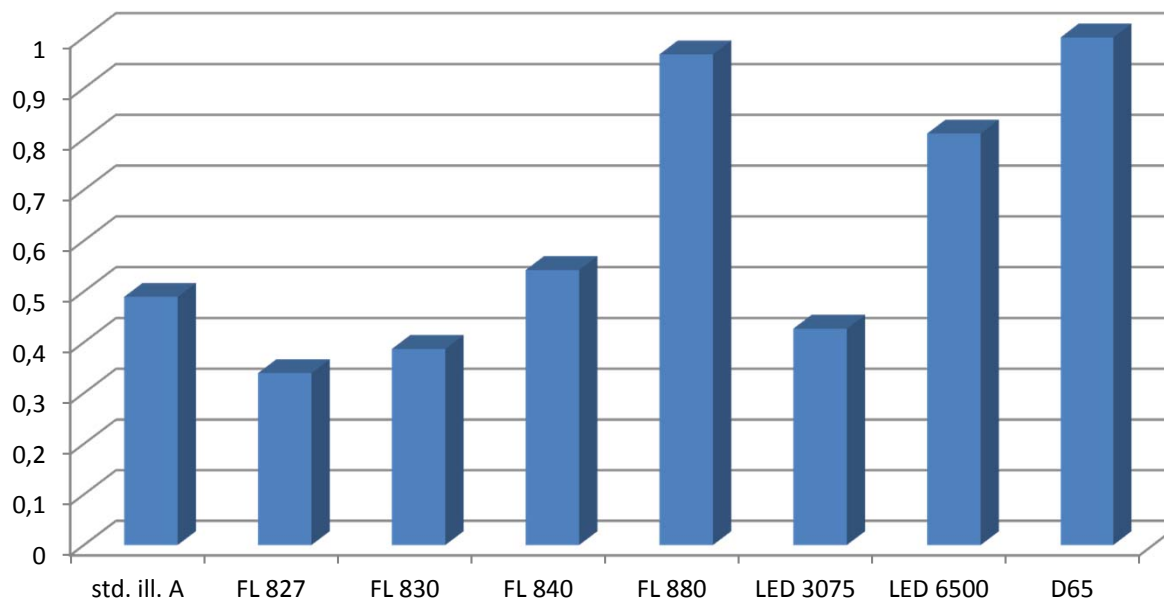
Illuminant	Photopic illuminance $E_v$	Melanopic daylight-equivalent illuminance $E_{v, mel, D65}$	Conversion factor $m_{v, mel, D65} = E_{v, mel, D65} / E_v$	Melanopic irradiance $E_{e, mel}$	melanopic lux (Lucas' Irradiance Toolbox)
Std. illuminant A (CCT= 2856 K)	1000 lx	496 lx	0,496	0,658 W/m <sup>2</sup>	547
Fluorescent type CIE F10 (FL, CCT= 5000 K)	1000 lx	683 lx	0,683	0,906 W/m <sup>2</sup>	754
Fluorescent type CIE F12 (FL, CCT= 3000 K)	1000 lx	404 lx	0,404	0,535 W/m <sup>2</sup>	445
<b>Std. illuminant D65 (daylight CCT= 6500 K)</b>	<b>1000 lx</b>	<b>1000 lx</b>	<b>1,000</b>	1,326 W/m <sup>2</sup>	<b>1104</b>
illuminant P (candle light)	1000 lx	267 lx	0,267	0,355 W/m <sup>2</sup>	295
LED, white (CCT= 3075 K)	1000 lx	427 lx	0,427	0,553 W/m <sup>2</sup>	472
LED, white (CCT= 5400 K)	1000 lx	787 lx	0,787	1,044 W/m <sup>2</sup>	869
LED, white (CCT= 6535 K)	1000 lx	800 lx	0,800	1,062 W/m <sup>2</sup>	883
High CCT Fluorescent (CCT= 8000 K)	1000 lx	957 lx	0,957	1,269 W/m <sup>2</sup>	1056





# Melanopic photometric data

Conversion factor from photopic illuminance (in lx)  
to daylight equivalent illuminance  $E_{v, mel, D65}$  (in lx)



Characteristical property of light sources

Potential to elicit melanopic effects in comparison to daylight

# How to Make Studies Comparable ?

- Influence of Light on Sleepiness (KSS, see Metrics Report p. 33)

	Literature Source	N	Light Conditions	Light type	CCT (K)	Spectrum (± with peak)
KSS	Kräuchi 1997	9	5000 lx; Dim 8 lx	Fluorescent	4000 K	
	Cajochen 1998	8	5000 lx; Dim 8 lx	Fluorescent	4000 K	
	Rüger 2003	12	5000 lx Dim 10 lx	Fluorescent	5000 K	
	Cajochen 2005	10	12.1 $\mu\text{W}/\text{cm}^2$ ; 10.1 $\mu\text{W}/\text{cm}^2$ ; 0 lux	LED		460 ( $\pm 10\text{nm}$ ) 550 ( $\pm 10\text{nm}$ )
	Rüger 2005	12 24	5000 lx Dim 10 lx	Fluorescent	5000 K	
	Lockley 2006	16	12.1 $\mu\text{W}/\text{cm}^2$ ; 10.1 $\mu\text{W}/\text{cm}^2$ ;	LED		460 ( $\pm 10\text{nm}$ ) 550 ( $\pm 10\text{nm}$ )
	Cajochen 2011	13	110 lx 100 lx	Fluorescent LED	4775 K 6953 K	
	Smolders 2012	32	200 lx 4000 lx	Fluorescent	4600 K	
	Yokoi 2003	8	2800 lx 120 lx	Fluorescent	4000 K	
	Chellappa 2011	16	40 lx 40 lx 40 lx	Fluorescent	3000 K 6500 K 2500 K	
	Sivaji 2013	10	400 lux	Fluorescent	2700 K	

# How to Make Studies Comparable ?

- Influence of Light on Melatonin Suppression (see Metrics Report p. 33)

	Literature Source	N	Light Conditions	Light type	CCT (K)	Spectrum (± with peak)
Melatonin suppression	Bojkowski et al. 1987	5	1,300, 2500 lux	Fluorescent	4000-5500 K	
	Brainard et al. 2001	72	0.03-100x10 <sup>12</sup> photons/cm <sup>2</sup>	Fluorescent		420-600 nm
	Brainard et al. 2015	24	1-800 μW/cm <sup>2</sup>	Xenon arc lamp	4000 K, 17000 K	400-500 nm
	Cajochen et al. 2005	10	10.0-12.1 μW/cm <sup>2</sup>	Fluorescent		460-550 nm
	Cajochen et al. 2011	13	100 lux	Xenon arc lamp		410-500 nm
	Hanifin et al. 2006	8	1.9x10 <sup>18</sup> photons/cm <sup>2</sup>	LED, Fluorescent		460-700 nm
	Herljevic et al. 2005	34	3.8-62 μW/cm <sup>2</sup>	Xenon arc lamp		456-560 nm
	Higuchi et al. 2007	10	1000 lux	Metal halide arc using Monochromatic filters	4200 K	
	Kozaki et al. 2008	12	200 lux	Fluorescent	2300-5000 K	
	Lavoie et al. 2003	14	bright white 300 lux; dim red <15 lux	Fluorescent	3500 K (assumed)	
	Lewy et al. 1980	6	500 lux; 1500-2500 lux	Fluorescent; Incandescent	3500 K (assumed); 2700 K (assumed)	
	Lockley et al. 2006	16	10.0-12.1 μW/cm <sup>2</sup>	Xenon arc lamp		460-555 nm
	McIntyre et al. 1989	13	200-300 lux	Fluorescent	3500 K (assumed)	
	Phipps-Nelson et al. 2009	8	1 lux	LED		460-640 nm
	Revell & Skene 2007	11	2.1-10.4 μW/cm <sup>2</sup>	Ultra high pressure Mercury lamp		479 nm
	Revell et al. 2010	12	19.1-36 μW/cm <sup>2</sup>	Fluorescent	4000 K, 17000 K	437-532 nm
	Rüger et al. 2003	18	11.8 μW/cm <sup>2</sup>	Xenon arc lamp		480 nm
	Santhi et al. 2011	22	225-700 lux	Fluorescent	4500 K (assumed)	
	Thapan et al. 2001	22	0.7-65.0 μW/cm <sup>2</sup>	Metal halide arc using Monochromatic filters		424-548 nm
	Wahnschaffe et al. 2013	9	130 lux, 500 lux	Fluorescent, metal halogenid, dielectric inhibited	2000-6000 K	
	West et al. 2011	8	0.09-562 lux	blue LED; white fluorescent	4000 K	469 nm
	Whitmore et al. 2002	10	20-1000 lux	Fluorescent	3500 K (assumed)	530 nm
	Wirz-Justice et al. 2004	9	5000 lux	Fluorescent (assumed)	4000 K (assumed)	
	Wright & Lack 2001	15	130 μW/cm <sup>2</sup>	LED		470-660 nm
	Wright et al. 2000	62	5000 lux	Halogen and light boxes	5000 K (assumed)	
	Wright et al. 2001	66	2000 lux	LED		460-560 nm
	Zeitzer et al. 2000	23	3-9100 lux	Fluorescent	3500 K (assumed)	

27 studies

>> 100 different lighting conditions

No direct comparability of photometric data

# HCL Toolkit

- Assessment of different lighting conditions by rescaling to melanopic and other  $\alpha$ -opic illuminance

quick instruction: Click "help" button in Cell W1 for detailed help.  
And read the help file! [Open help file](#)

1. Select the type of light source in cell A5 from the dropdown list.  
2. Enter a Color Temperature in cell A8 if required  
3.1 Enter a photometric intensity (e.g. lux) in cell A11  
3.2 alternatively enter power density in cell A13  
3.3 alternatively enter photon density in cell A15  
! always click "enter" or leave the selected cell after entering data!  
4. Click button "Calculate" on right hand side of selected input cell  
! calculation is not started automatically after modifying input  
5. read results in columns T-V  
check comments in individual cells for more instructions.

provided to lightingforpeople by Dieter Lang  
dieter.lang@osram.com, phone +49 89 6210 3321

OSRAM

Input		Results		read comment
select type of light source		DIN SPEC 5031-100		
Daylight 4500-8000K	<input checked="" type="checkbox"/> print results to protocol page	scotopic illuminance [lx]	1,3265 mW/m <sup>2</sup>	0,906
enter Color Temperature (CCT)	open results_protocol >	melanopic daylight equivalent efficiency factor	melanopic daylight equivalent illuminance MDEI [lx]	0,297959094
6500		LPW (photopic) luminous efficacy of radiation	1,000	500,00
		203,5 lm/W		
		WD CENTC SI & CIE compliant	results irradiance [Lucas, CIE, 2015]	Results TiNS [Lucas et al., 2014]
		melanopic daylight equivalent illuminance MDEI [lx]	melanopic irradiance [ $\mu$ W/cm <sup>2</sup> ]	"melanopic lux"
enter illuminance in cell A11	select unit for input	500,00	66,32	551,89
500,00	calculate > lx	L-cone daylight equivalent illuminance [lx]	irradiance [ $\mu$ W/cm <sup>2</sup> ]	"erythroptic lux"
alternatively enter irradiance in cell A13		500,00	81,45   85,87	497,07
245,692928	calculate > $\mu$ W/cm <sup>2</sup>	M-cone daylight equivalent illuminance [lx]	irradiance [ $\mu$ W/cm <sup>2</sup> ]	"chloropic lux"
alternatively enter photon density in cell A15		500,02	72,79   83,91	520,29
7,003E+14	calculate > Photons/(cm <sup>2</sup> * sec)	S-cone daylight equivalent illuminance [lx]	irradiance [ $\mu$ W/cm <sup>2</sup> ]	"cyanopic lux"
		500,15	40,88   40,12	531,60

Main user-defined results\_protocol sample spectra Help

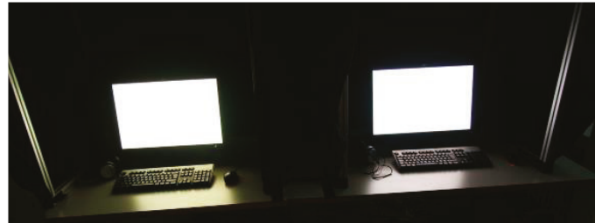
## 1. Assessment of Studies

- Select light source
- Select parameters (CCT, ...)
- Enter intensity
- Start calculation
- Read results ( $\alpha$ -opic data)

## 2. Lighting Design

- Select light source
- Select parameters (CCT, ...)
- Enter target data ( $\alpha$ -opic data)
- Start calculation
- Read required light intensity

## Example 1 / Melatonin Suppression



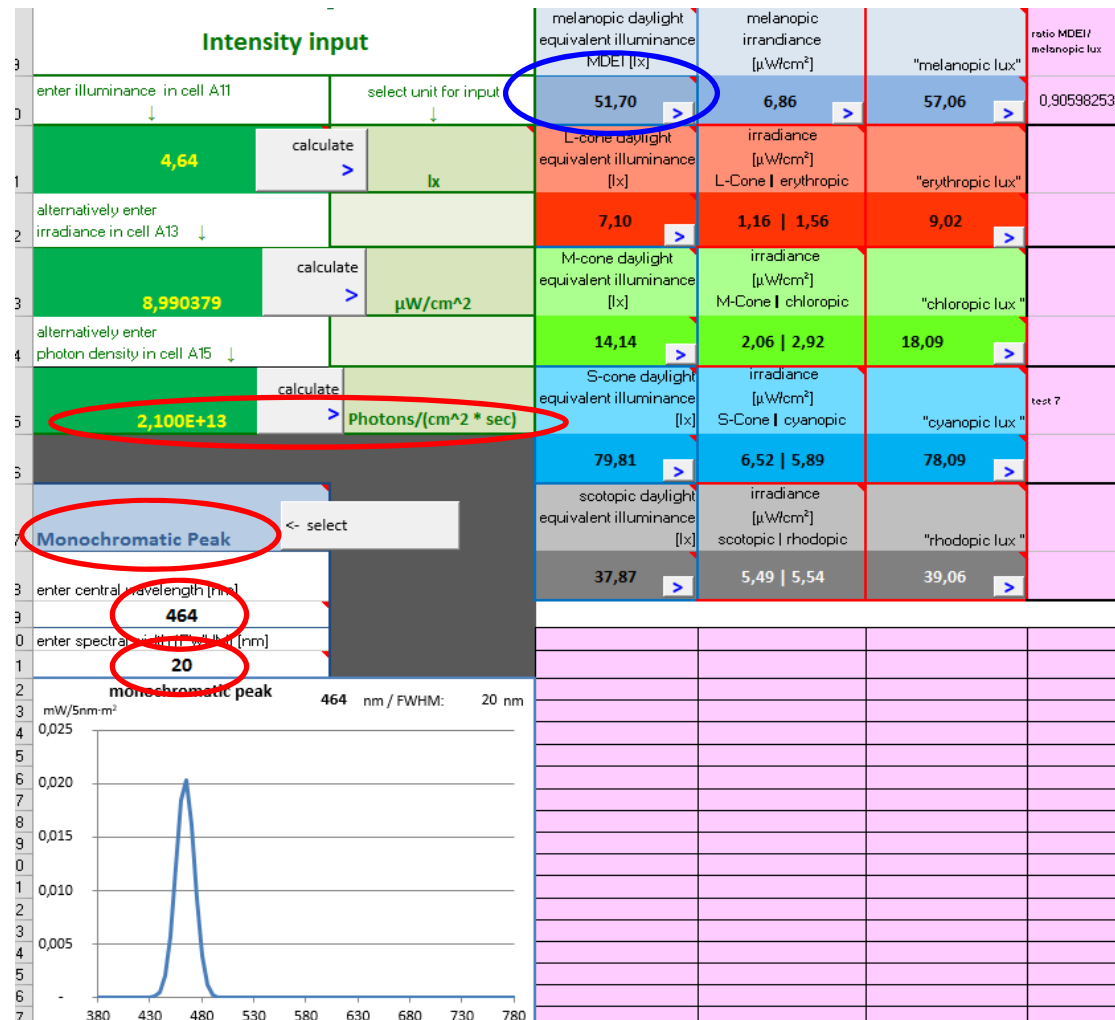
5 h exposure to computer screen

Blue light:  $\sim 464 \text{ nm} \pm 10 \text{ nm}$   
 $2.1 \times 10^{13} \text{ photons}/(\text{cm}^2 \times \text{s})$

→ Significant influence on melatonin  
 and subjective alertness

Cajochen C, Frey S, Anders D, Späti J, Bues M, Pross A, Mager R, Wirz-Justice A, Stefani O. Evening exposure to a light-emitting diodes (LED)-backlit computer screen affects circadian physiology and cognitive performance. *J Appl Physiol* 110: 1432–1438, 2011. First published March 17, 2011; doi:10.1152/japplphysiol.00165.2011.—Many people spend an increasing amount of time in front of computer screens equipped with light-emitting diodes (LED) with a short wavelength (blue range). Thus we investigated the repercussions on melatonin (a marker of the circadian clock), alertness, and cognitive performance levels in 13 young male volunteers under controlled laboratory conditions in a balanced crossover design. A 5-h evening exposure to a white LED-backlit screen with more than twice as much 464 nm light emission [irradiance of  $0.241 \text{ Watt}/(\text{steradian} \times \text{m}^2)$  [ $\text{W}/(\text{sr} \times \text{m}^2)$ ],  $2.1 \times 10^{13} \text{ photons}/(\text{cm}^2 \times \text{s})$ , in the wavelength range of 454 and 474 nm] than a white non-LED-backlit screen [irradiance of  $0.099 \text{ W}/(\text{sr} \times \text{m}^2)$ ,  $0.7 \times 10^{13} \text{ photons}/(\text{cm}^2 \times \text{s})$ , in the wavelength range of 454 and 474 nm] elicited a significant suppression of the evening rise in endogenous melatonin and subjective as well as objective sleepiness, as indexed by a reduced incidence of slow eye movements and EEG low-frequency activity (1–7 Hz) in frontal brain regions. Concomitantly, sustained attention, as determined by the GO/NOGO task; working memory/attention, as assessed by “explicit timing”; and declarative memory performance in a word-learning paradigm were significantly enhanced in the LED-backlit screen compared with the non-LED condition. Screen quality and visual comfort were rated the same in both screen conditions, whereas the non-LED screen tended to be considered brighter. Our data indicate that the spectral profile of light emitted by computer screens impacts on circadian physiology, alertness, and cognitive performance levels. The challenge will be to design a computer screen with a spectral profile that can be individually programmed to add timed, essential light information to the circadian system in humans.

# Example 1 / LED Computer Screen



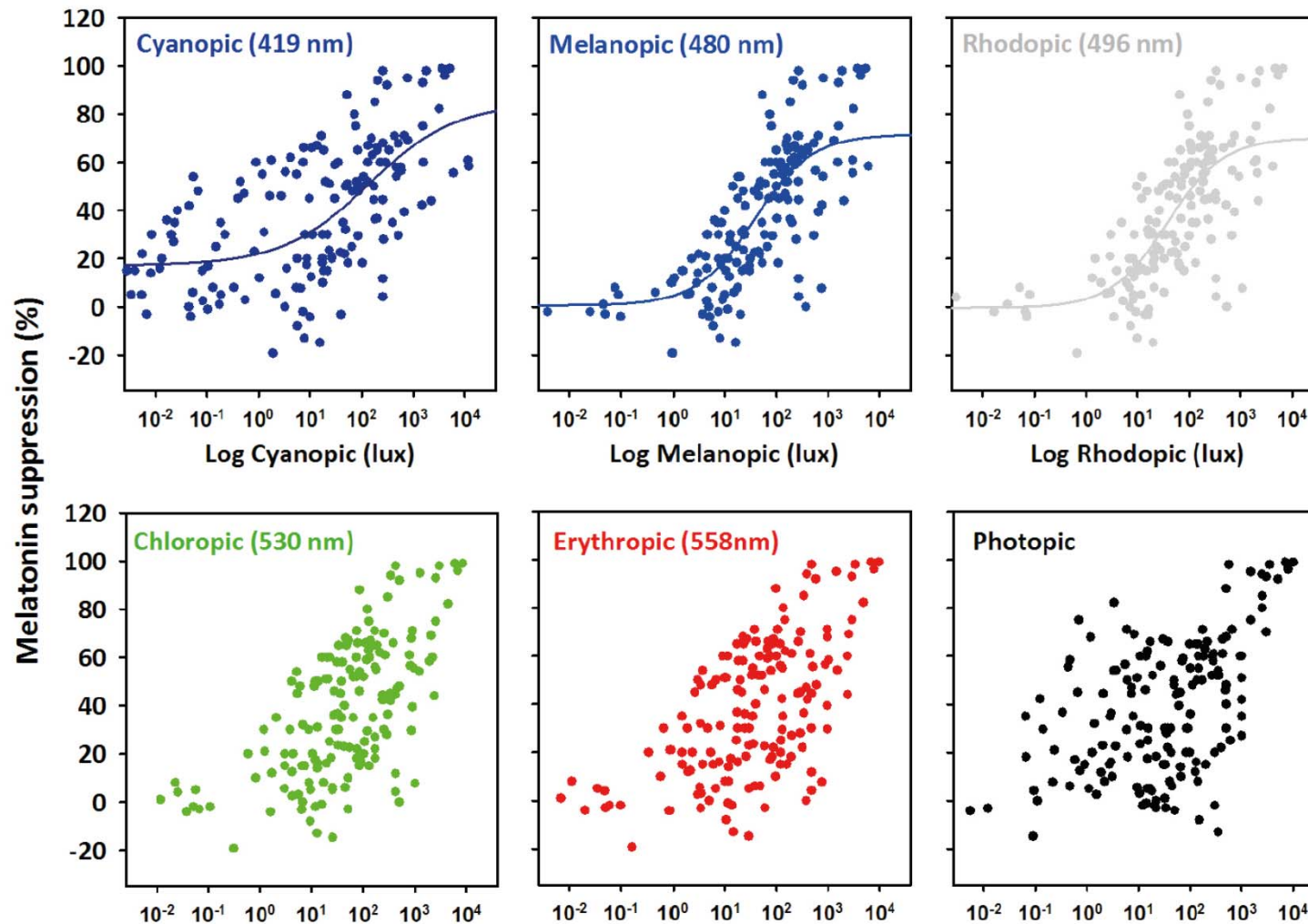
This example is shown live using the HCL-Toolkit

Blue light  $\sim 464 \pm 10 \text{ nm}$   
 $2.1 \times 10^{13} \text{ photons}/\text{cm}^2$

→ MDEI = 51,7 lx



# Correlations become visible after rescaling



## Example 2 / Nursing Home for Elderly

<p>quick instruction: Click "help" button in Cell W1 for detailed help.</p> <p>And read the help file! <span>Open help file</span></p> <p>1. Select the type of light source in cell A5 from the dropdown list.</p> <p>2. Enter a Color Temperature in cell A8 if required</p> <p>3.1. Enter a photometric intensity (e.g. lux) in cell A11</p> <p>3.2. alternatively enter power density in cell A13</p> <p>3.3. alternatively enter photon density in cell A15</p> <p>I always click "enter" or leave the selected cell after entering data!</p> <p>4. Click button "Calculate" on right hand side of selected input cell</p> <p>I calculation is not started automatically after modifying input</p> <p>5. read results in columns T-V</p> <p>check comments in individual cells for more instructions.</p>			<h1>Human Centric Lighting Toolkit</h1> <h2>V14.21</h2> <div><p>CONNECTING OPPORTUNITIES FOR INNOVATION</p></div> <p>provided to lightingforpeople by Dieter Lang dieter.lang@osram.com, phone +43 89 6213 3321</p> <p><b>OSRAM</b> </p>			<p>?</p> <p>?</p> <p>?</p> <p>Help</p> <p>?</p> <p>?</p> <p>?</p>
1			S/P-ratio	Results DIN SPEC 5031-100	read comment	
2	Input	replace this comment with own comment for protocol page	0,961	melanopic efficacy of luminous radiation	luminous efficiency of radiation	
3	select type of light source	<input checked="" type="checkbox"/> print results to protocol page	scotopic illuminance [lx]	1.2692 mW/lm	0,867	
4	↓	open results_protocol >	-/-	melanopic daylight equivalent efficiency factor	melanopic daylight equivalent illuminance MDEI [lx]	
5	Fluorescent standard 2000-18500K		LPW (photopic) luminous efficacy of radiation	0,957	956,79	
6			290,4 lm/W			
7	enter Color Temperature (CCT)		WD CENTC SI & CIE compliant	results irradiance [Lucas, CIE, 2015]	Results TiNS [Lucas et al., 2014]	
8	8000		melanopic daylight equivalent illuminance MDEI [lx]	melanopic irradiance [μW/cm²]	ratio MDEI / melanopic lux	
9	Intensity input		956,79	126,92	"melanopic lux"	
10	enter illuminance in cell A11	select unit for input	calculate	1056,08	0.9059823	
11	1000,00	calculate	L-Cone daylight equivalent illuminance [lx]	irradiance [μW/cm²] L-Cone I erythropic	"erythropic lux"	
12	alternatively enter irradiance in cell A13		986,53	160,70   167,23	968,00	
13	344,294372	calculate	M-cone daylight equivalent illuminance [lx]	irradiance [μW/cm²] M-Cone I chloropic	"chloropic lux"	
14	alternatively enter photon density in cell A15		1002,43	145,94   166,41	1031,83	
15	9,063E+14	calculate	S-cone daylight equivalent illuminance [lx]	irradiance [μW/cm²] S-Cone I cyanopic	"cyanopic lux"	
		Photons/(cm^2 * sec)			test 7	

This example is shown live using the HCL-Toolkit

Positive effects shown for lighting conditions  
1000 lx, 8000 K,  
fluorescent lamp

→  $MDEI = 956,79 \text{ lx}$

## Example 2 / Nursing Home for Elderly

**pick instruction: Click "help" button in Cell W1 for detailed help. And read the help file!** [Open help file](#)

1. Select the type of light source in cell A5 from the dropdown list.  
2. Enter a Color Temperature in cell A8 if required  
3.1. Enter a photometric intensity (e.g. lux) in cell A11  
3.2. alternatively enter power density in cell A13  
3.3. alternatively enter photon density in cell A15  
! always click "enter" or leave the selected cell after entering data!  
4. Click button "Calculate" on right hand side of selected input cell  
! calculation is not started automatically after modifying input  
5. read results in columns T-V  
check comments in individual cells for more instructions.

**Human Centric Lighting Toolkit V14.21**

provided to lightingforpeople by: Dieter Lang  
dieter.lang@osram.com, phone +49 89 6213 3321

**OSRAM**

**Input**

replace this comment with own comment for protocol page

select type of light source

LED white, 2900-7000K

enter Color Temperature (CCT)

6500

**Intensity input**

enter illuminance in cell A11

1196,15

calculate

alternatively enter irradiance in cell A13

382,405183

calculate

alternatively enter photon density in cell A15

1,040E+15

calculate

**Results**

DIN SPEC 5031-100

SP-ratio

0,838

scotopic illuminance [lx]

1.0610 mW/lm

0,725

melanopic efficacy of luminous radiation

melanopic factor  $a_{mel,v}$

0,457975365

melanopic daylight equivalent efficiency factor

melanopic daylight equivalent illuminance MDEI [lx]

956,79

LPW (photopic) luminous efficacy of radiation

312,8 lm/W

WD CENTC SI & CIE compliant

results irradiance [Lucas, CIE, 2015]

Results TiNS [Lucas et al., 2014]

melanopic daylight equivalent illuminance MDEI [lx]

956,79

melanopic irradiance [ $\mu\text{W}/\text{cm}^2$ ]

126,92

"melanopic lux"

1056,08

ratio MDEI / melanopic lux

0,905982537

L-cone daylight equivalent illuminance [lx]

1171,73

irradiance [ $\mu\text{W}/\text{cm}^2$ ]

190,87 | 197,62

"erythropic lux"

1143,93

M-cone daylight equivalent illuminance [lx]

1149,39

irradiance [ $\mu\text{W}/\text{cm}^2$ ]

167,33 | 189,42

"chloropic lux"

1174,49

S-cone daylight equivalent illuminance [lx]

1207,96

irradiance [ $\mu\text{W}/\text{cm}^2$ ]

98,74 | 95,34

"cyanopic lux"

1263,41

test 7

This example is shown live using the HCL-Toolkit

Now change to LED lighting, white light, 6500 K

MDEI = 956,79lx

Start backward calculation

→ 1196,15 lx

Use this as target value for lighting design with 6500 K LED lighting.

# Summary

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- Metrics to assess light with respect to its non-visual effects has been developed
- Large number of studies has been made comparable by re-scaling their light settings to  $\alpha$ -opic irradiance
- Concept of Melanopic daylight equivalent illuminance (MDEI) has been applied to compare light settings to natural daylight
- For most studies MDEI gives the best correlation coefficients to the expected effects.
- Scientist need to be challenged for a better and more complete description of light settings in studies in order to guarantee comparability and reproducibility.
- A tool has been developed to allow retrospective comparability and lighting design in advance of studies



# Thanks for your attention!

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