Response to the American Medical Association (AMA) report, "Human and Environmental Effects of Light Emitting Diode Community Lighting"

Mark S. Rea, PhD
Mariana G. Figueiro, PhD
Lighting Research Center
Rensselaer Polytechnic Institute

Partner-Alliance Event
March 15, 2017

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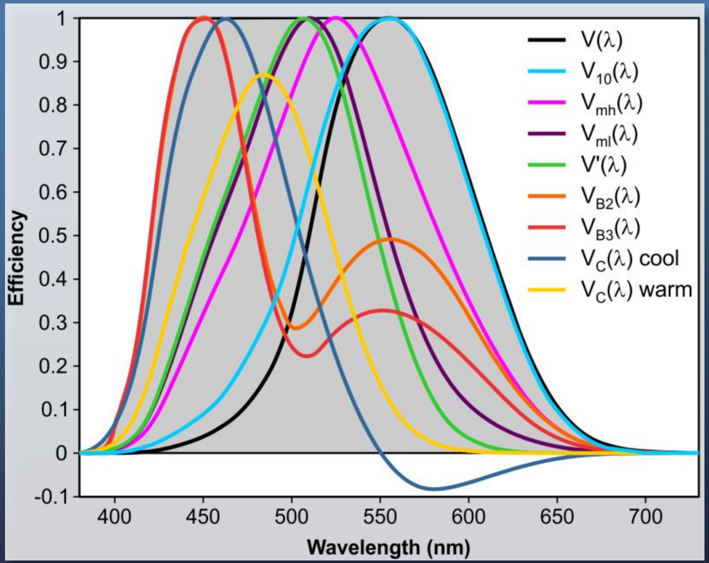
Why do we light?

- Visual performance
  - Assembly, reading, accounting
- Safety – crash avoidance
  - Vehicle-to-vehicle – on-axis judgement
  - Vehicle-to-pedestrian or bicycle – off-axis detection
- Security – sense of safety
  - Scene brightness
- Quality of life
  - Circadian entrainment



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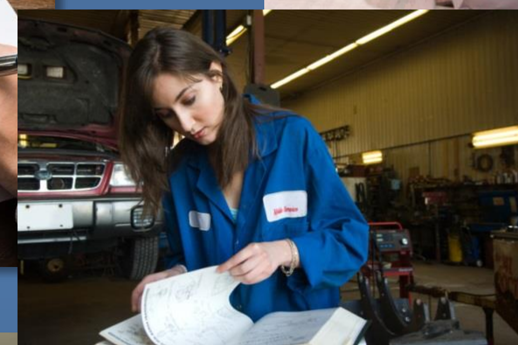
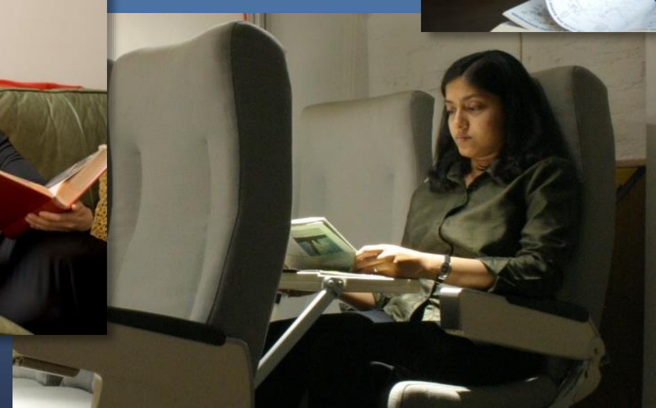
Why do we light?

- Assembly, reading, accounting





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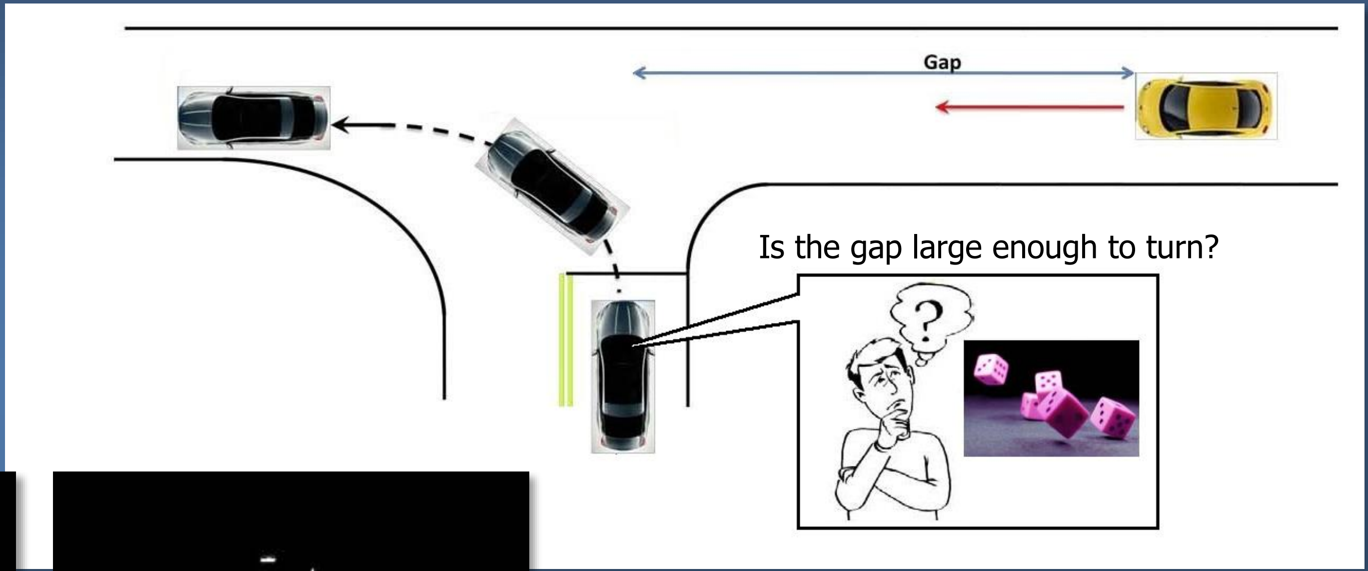
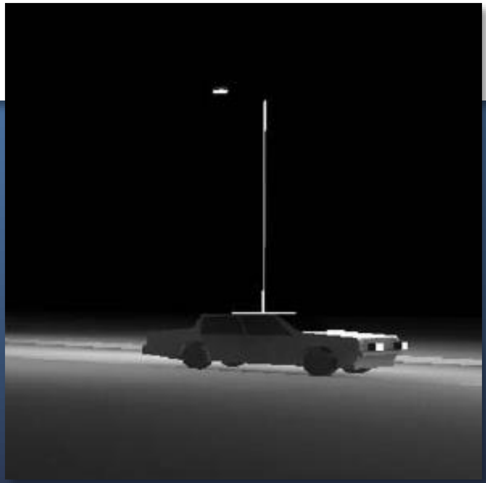
Why do we light?

Most crashes are vehicle-vehicle at conflict points (intersections)



Adapted from connectedvehicle.challenge.gov



Crash avoidance

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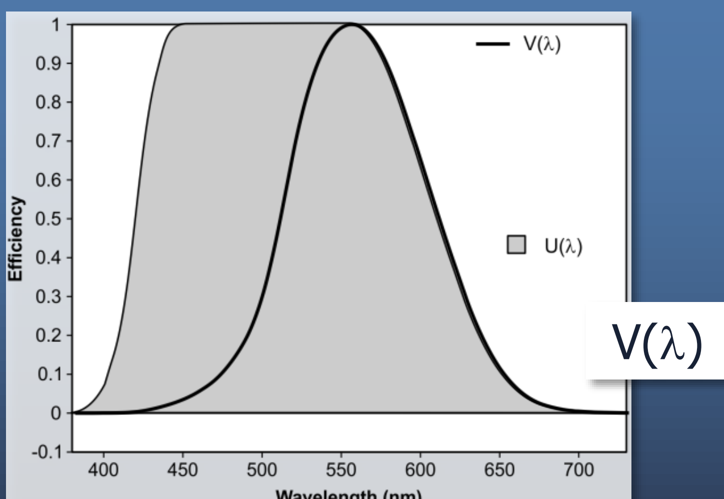
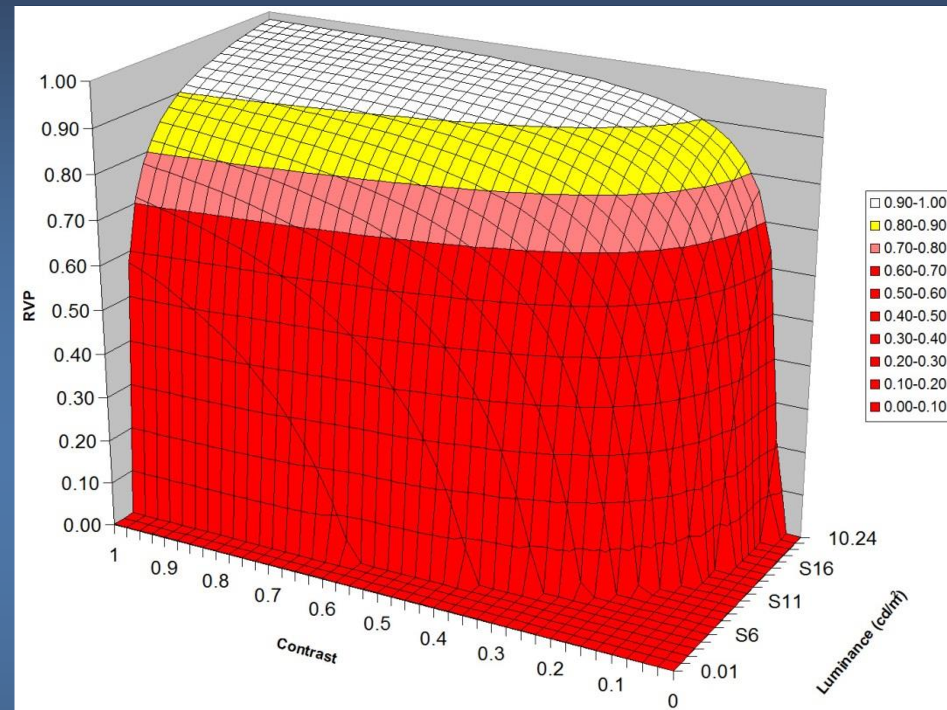
Analyzing on-axis visibility

- Apply relative visual performance (RVP) model
- Contrast and background luminance based upon V(λ)





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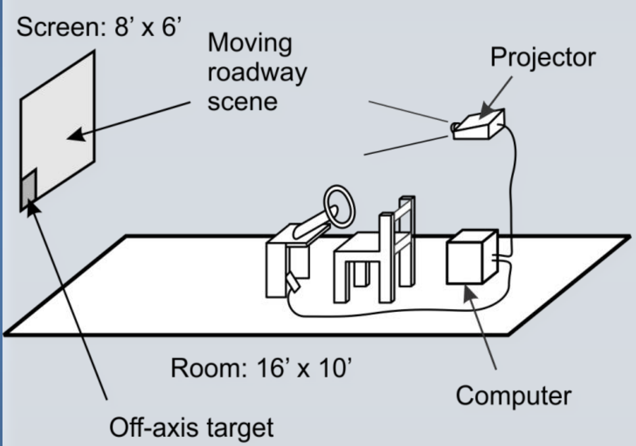
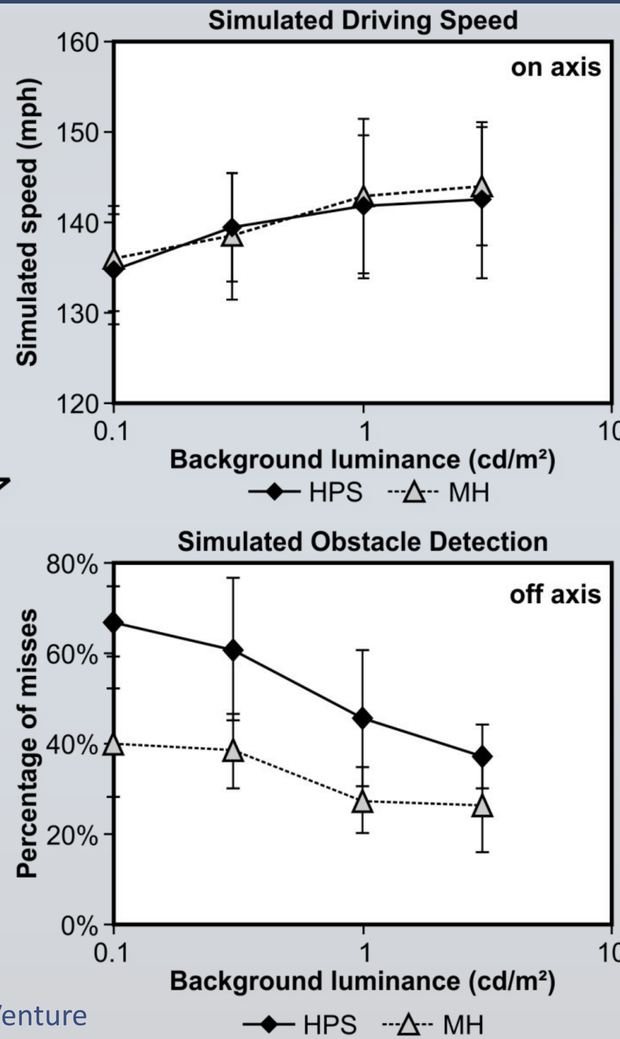
Driving performance – on- and off-axis



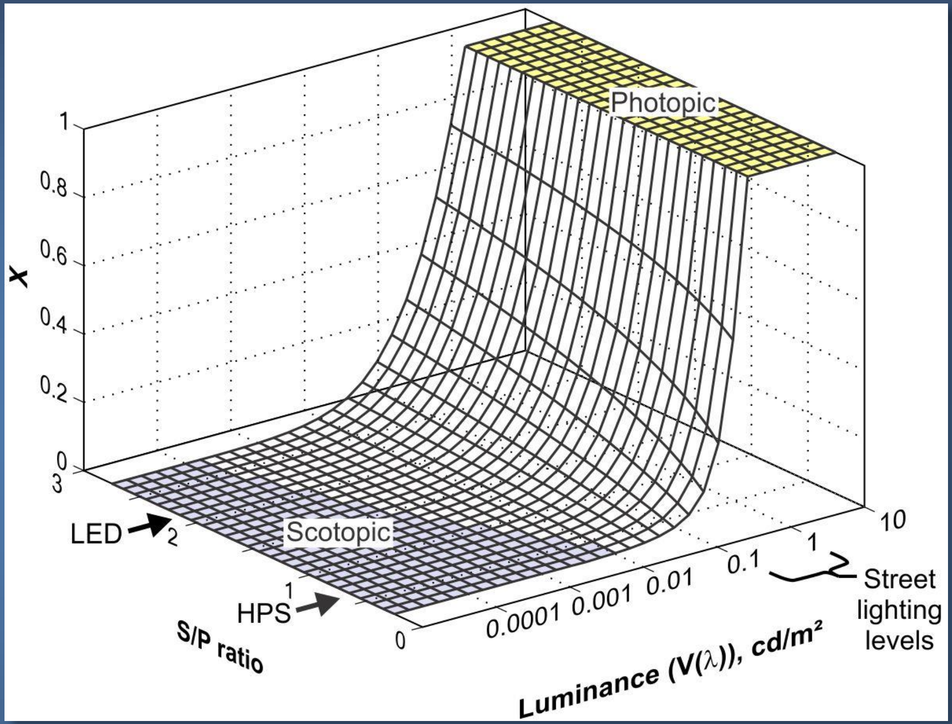


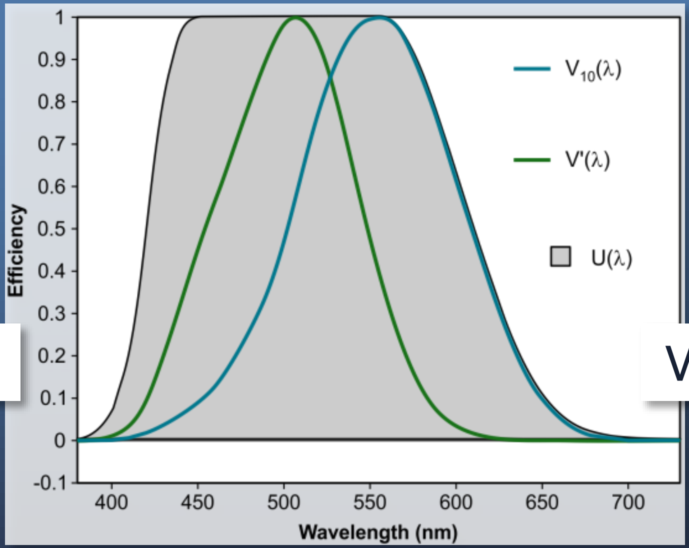
Bullough and Rea 2000

Sponsors: DOE, GE, OSRAM Sylvania, Philips, Venture

Analyzing off-axis visibility

- Apply unified system of photometry
- Adaptation level based upon $V'(\lambda)$ and $V_{10}(\lambda)$





V′(λ)

$V_{10}(\lambda)$

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Why do we light?

- University of Washington

  Three campus parking lots
  - High pressure sodium
  - Metal halide
  - LED

To feel safe

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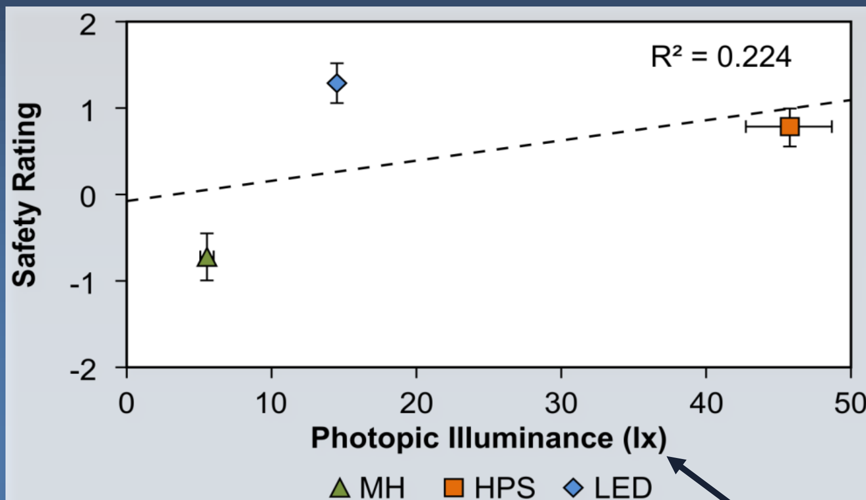
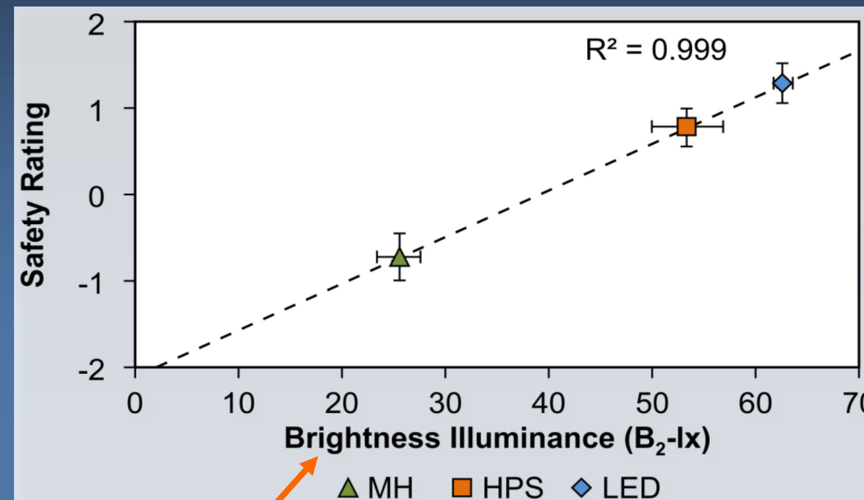
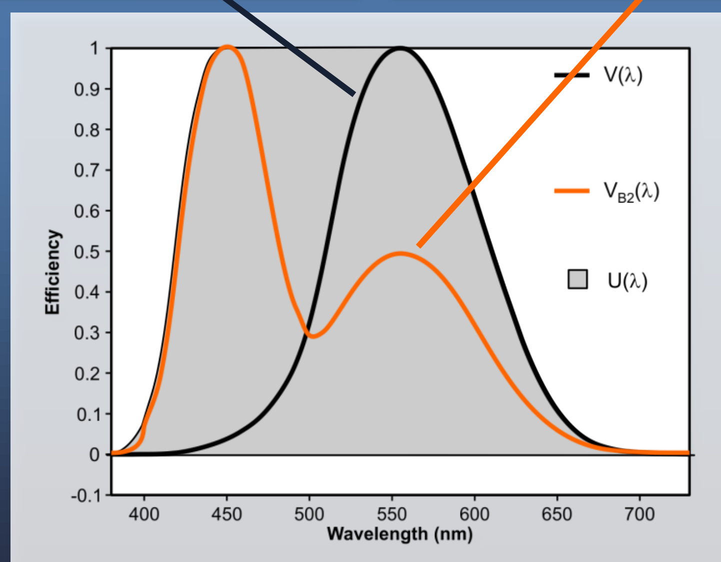
Analyzing scene brightness judgments





Scene brightness ratings are proportional to safety ratings



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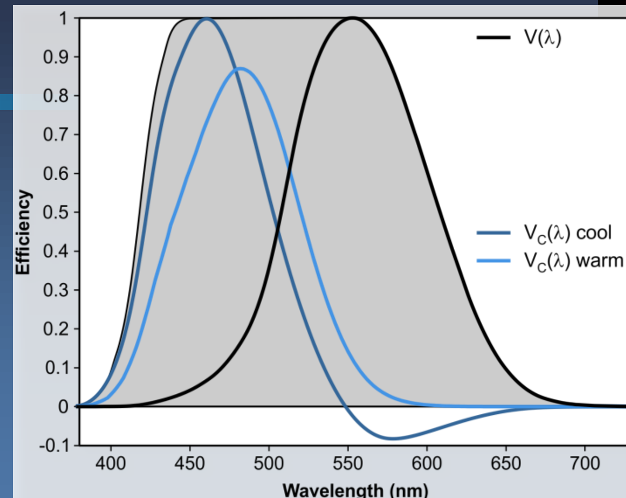
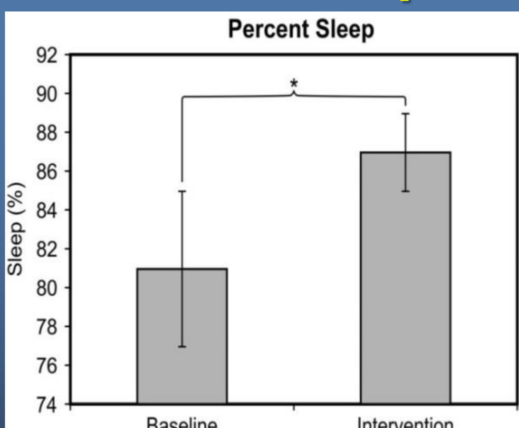
Why do we light?

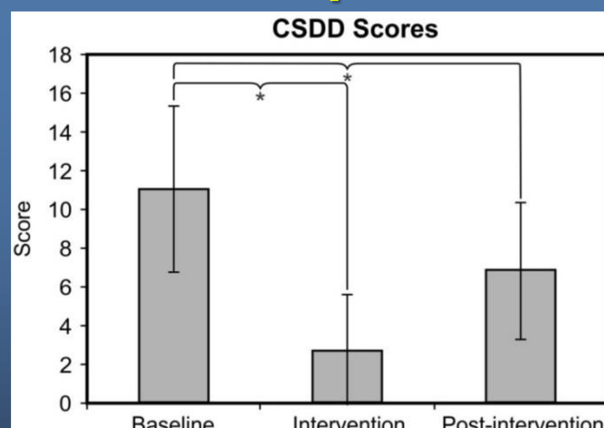
- Improve quality of life
  - Senior facilities



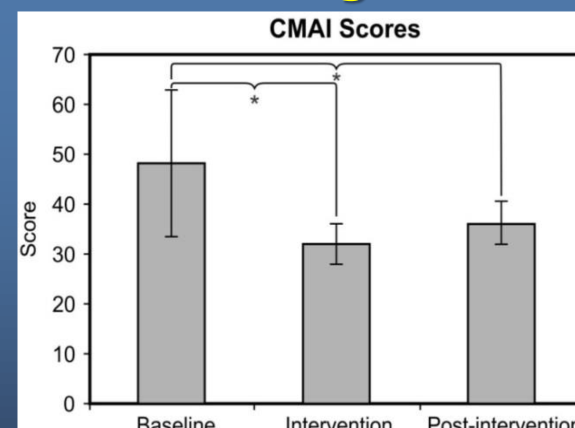
Better Sleep



Less Depression



Reduced Agitation

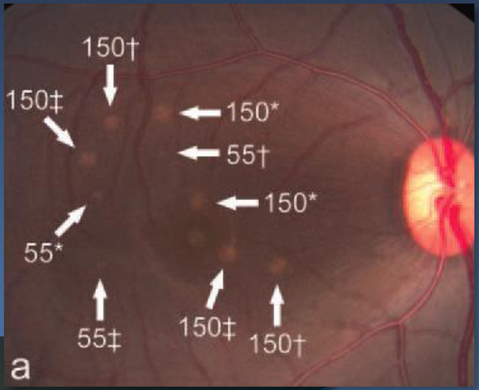


Sponsor: National Institute on Aging (R01AG034157)

Figueiro M, Plitnick B and Rea M. Research Note: A self-luminous light table for persons with Alzheimer's disease. *Light Res Technol*. 2015: 1477153515603881.

Potential negative, collateral consequences

- Blindness from blue light hazard
- Glare
  - Disability
  - Discomfort
- Circadian disruption and melatonin suppression



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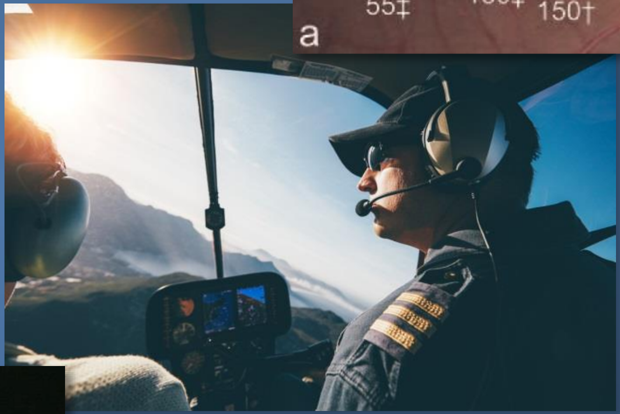

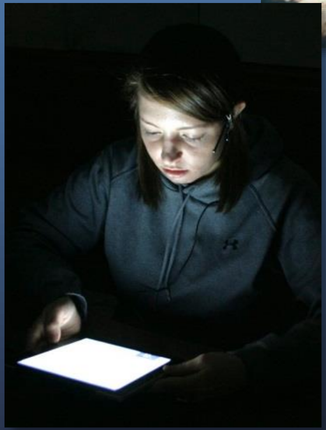

* Morgan, JIW et al. 2008. Light-induced retinal changes observed with high-resolution autofluorescence imaging of the retinal pigment epithelium. *Investigative Ophthalmology & Visual Science,* 49:8, 3715-3729

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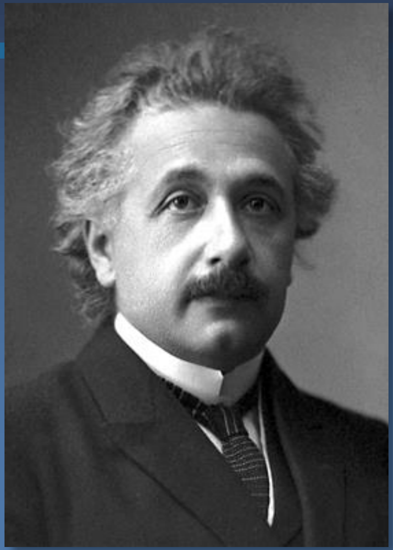
Critical considerations before we start



"Everything should be made as simple as possible, but not simpler."

A. Einstein

- Appropriate metrics, quantities and units
  - *Not* "blue wavelengths" or CCT
- Use cases: exposure/dose (amount and duration)

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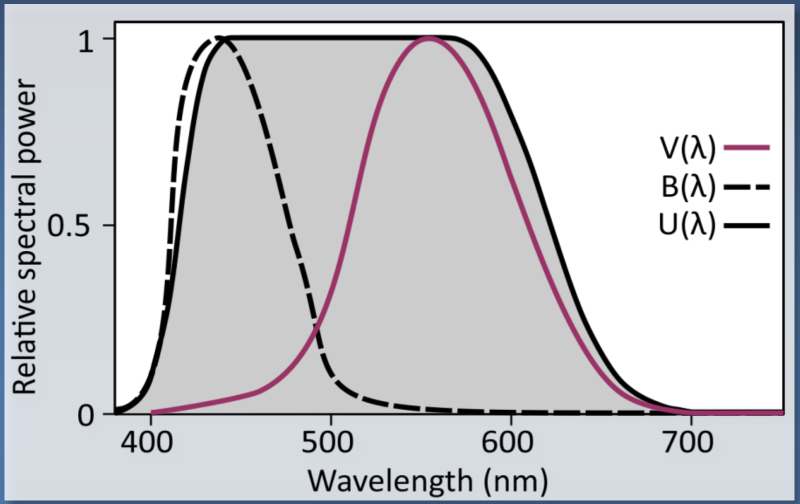
Blue light hazard

- What is blue light hazard?
  - Temporary or permanent loss of visual photoreceptor function following exposure to short-wavelength radiation imaged on the retina



V(λ) = Photopic
B(λ) = Blue light hazard
U(λ) = Universal luminous efficiency function

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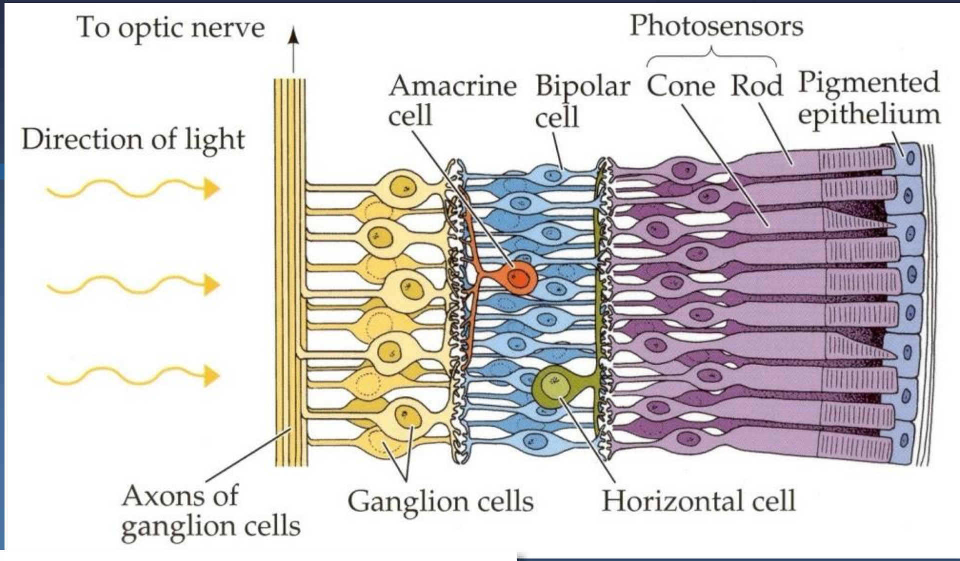
Pigment epithelium



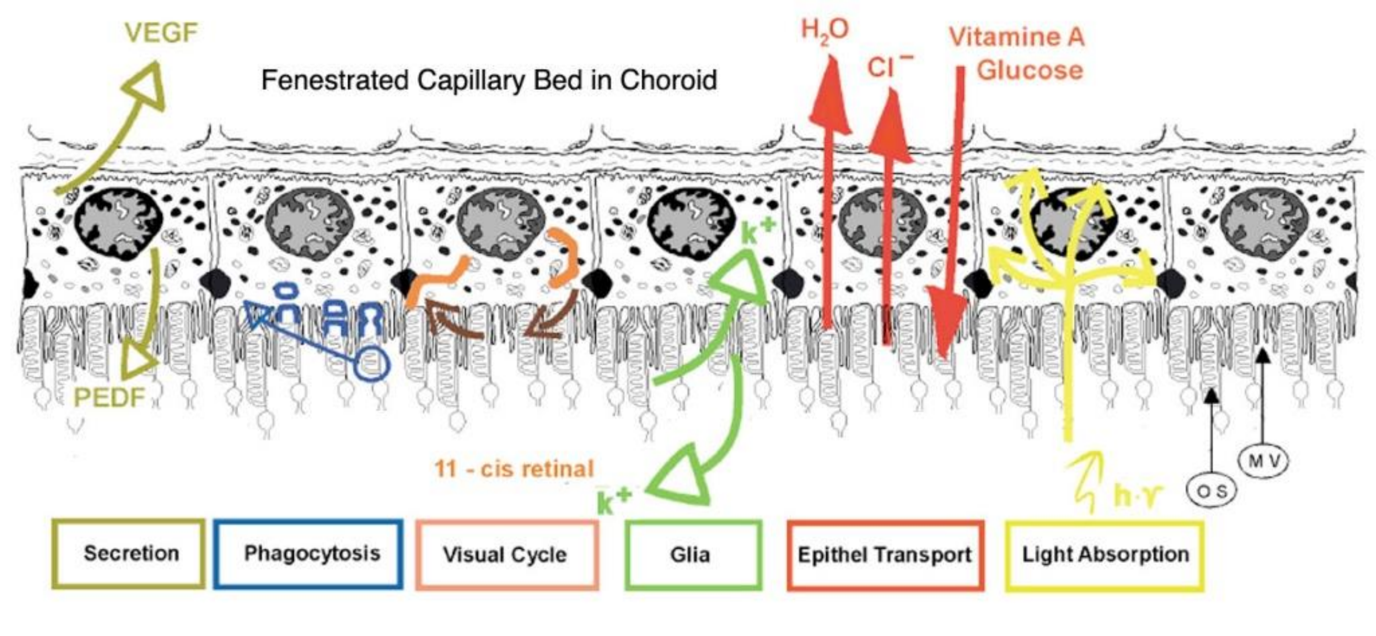


Figure 3. Summary diagram of the major functions of the RPE.

Blue light hazard

Depends on short-term (hours) cumulative **retinal irradiance** of short wavelength radiation (~400 to ~500 nm)

Retinal irradiance depends on:
- Source size
- Output power
- Optics (if any)

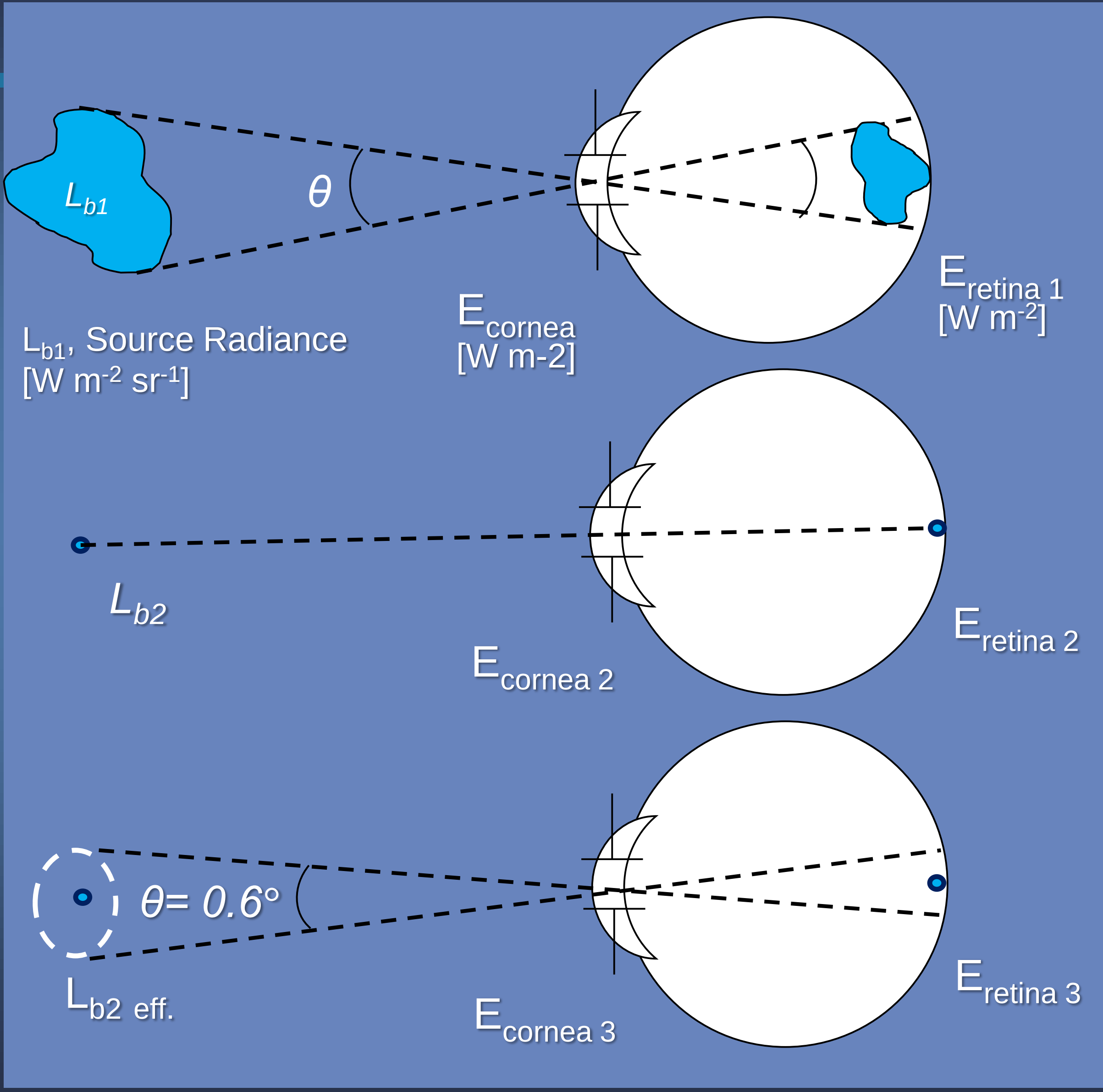
} **Radiance**

Not irradiance at the eye!

$E_{cornea\ 1} = E_{cornea\ 2} = E_{cornea\ 3}$

$E_{retina\ 1} < E_{retina\ 3} < E_{retina\ 2}$

$L_{b1} < L_{b2\ eff.} < L_{b2}$



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Blue light hazard comparison

Source	Actual Luminance (cd/m²)	Effective Luminance (cd/m²)	Blue Hazard Weighted Radiance, L_b ($W\ m^{-2}\ sr^{-1}$)	Permissible Exposure Time per CIE/IEC 62471
Noon sun	1,600,000,000	1,600,000,000	1,200,000	~ 1 s
Blue sky	4,000	4,000	6.2	Indefinite/44 hrs*
Blue LED light box (600 lux at eye)	9,000	9,000	60	Indefinite/4.6 hrs*
Blue LED 500mW, @ 0.5 m	5,100,000	170,000	2620	6.4 min†
Royal Blue LED 3W, @ 0.5 m	2,760,000	1,040,000	15,700	64 s
Fluorescent lamp (T8 RE 4100 K)	10,000	10,000	5.6	Indefinite/50 hrs*
Incandescent lamp filament @ 0.5 m	12,000,000	2,500,000	858	20 min†
White LED (3000 K) @ 0.5 m	17,000,000	1,000,000	388	43 min†
White LED (4000 K) @ 0.5 m	17,000,000	1,000,000	510	33 min†
White LED (6500 K) @ 0.5 m	17,000,000	1,000,000	858	20 min†

*Permissible exposure times (PET) are not defined for weighted radiance < 100 $W\ m^{-2}\ sr^{-1}$

†Permissible exposure times are not defined for small sources (<0.63°) for weighted irradiance < 1 $W\ m^{-2}$

PET = 278 hours/L_b for t < 2.78 hours or PET = 100 seconds/E_b for t < 100 seconds

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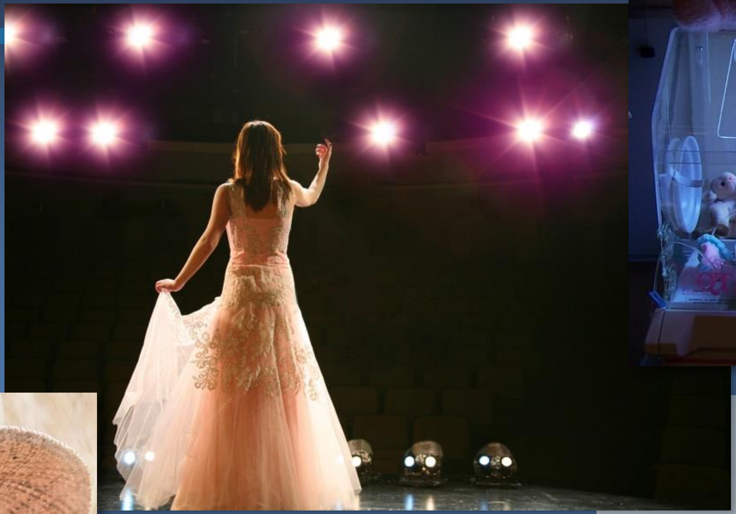
Use cases



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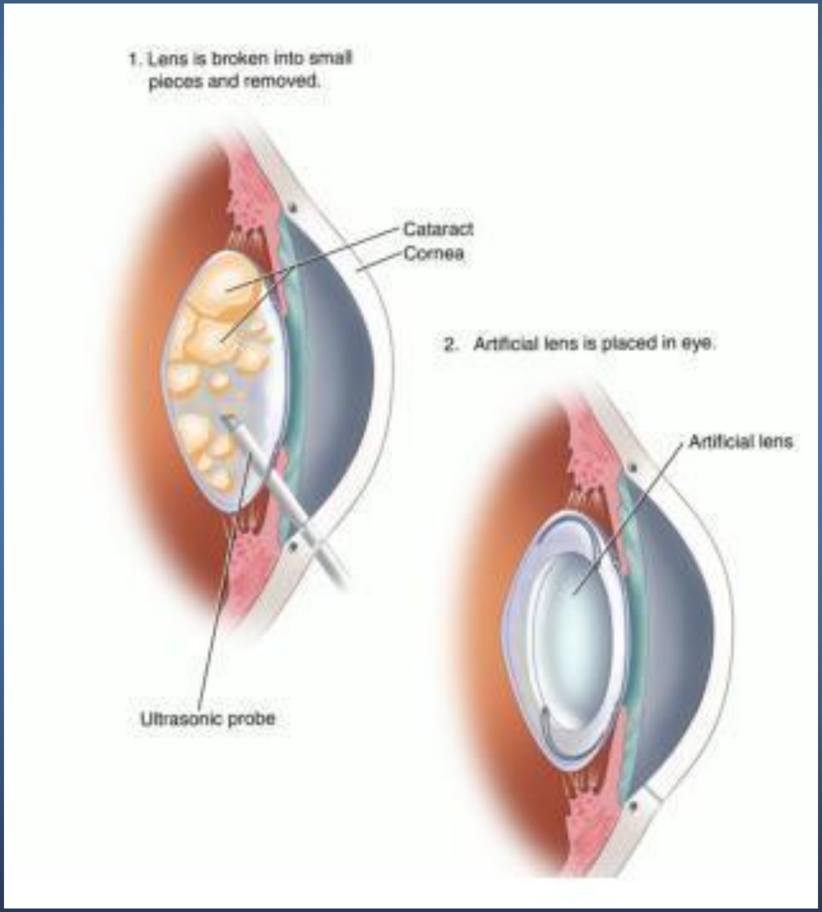
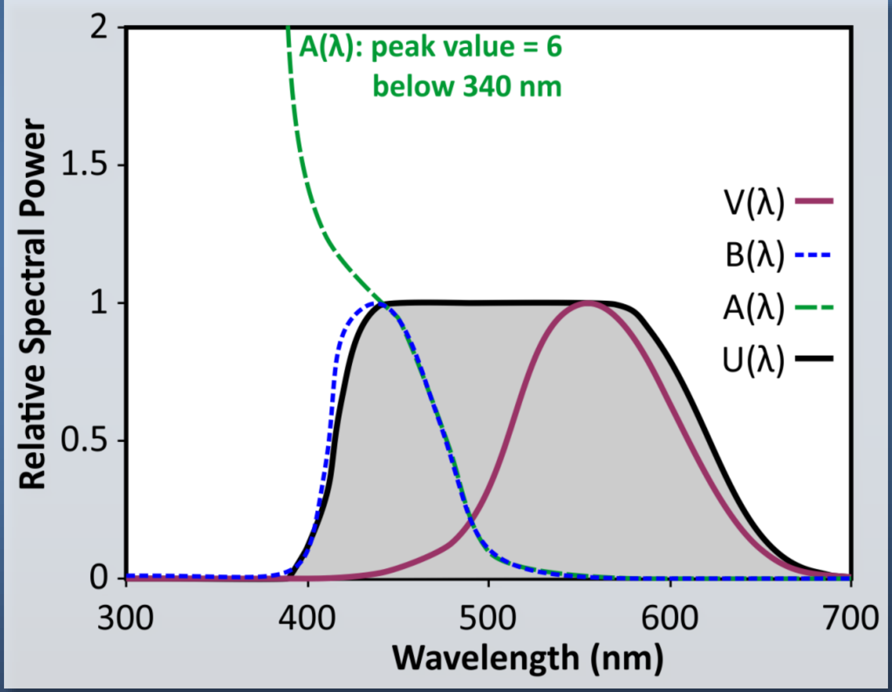
Aphakic lens

- After cataract surgery, prosthetic (aphakic) lens replacement





Blue light hazard comparison

Source	Actual Luminance (cd/m²)	Effective Luminance (cd/m²)	Blue Hazard Weighted Radiance, L_b ($W\ m^{-2}\ sr^{-1}$)	Permissible Exposure Time per CIE/IEC 62471 (Aphakic Eye Hazard per CIE/IEC 62471)
Noon sun	1,600,000,000	1,600,000,000	1,200,000	~ 1 s (~ 0.4 s)
Blue sky	4,000	4,000	6.2	Indefinite/44 hrs* (Indefinite/8 hrs*)
Blue LED light box (600 lux at eye)	9,000	9,000	60	Indefinite/4.6 hrs* (Indefinite/4.6 hrs*)
Blue LED 500mW, @ 0.5 m	5,100,000	170,000	2620	6.4 min (6.2 min) †
Royal Blue LED 3W, @ 0.5 m	2,760,000	1,040,000	15,700	64 s (62 s)
Fluorescent lamp (T8 RE 4100 K)	10,000	10,000	5.6	Indefinite/50 hrs* (Indefinite/33 hrs*)
Incandescent lamp filament @ 0.5 m	12,000,000	2,500,000	858	20 min (10 min) †
White LED (3000 K) @ 0.5 m	17,000,000	1,000,000	388	43 min (42 min) †
White LED (4000 K) @ 0.5 m	17,000,000	1,000,000	510	33 min (33 min) †
White LED (6500 K) @ 0.5 m	17,000,000	1,000,000	858	20 min (20 min) †

*Permissible exposure times (PET) are not defined for weighted radiance < 100 $W\ m^{-2}\ sr^{-1}$

†Permissible exposure times are not defined for small sources (<0.63°) for weighted irradiance < 1 $W\ m^{-2}$

PET = 278 hours/L_b for t < 2.78 hours or PET = 100 seconds/E_b for t < 100 seconds

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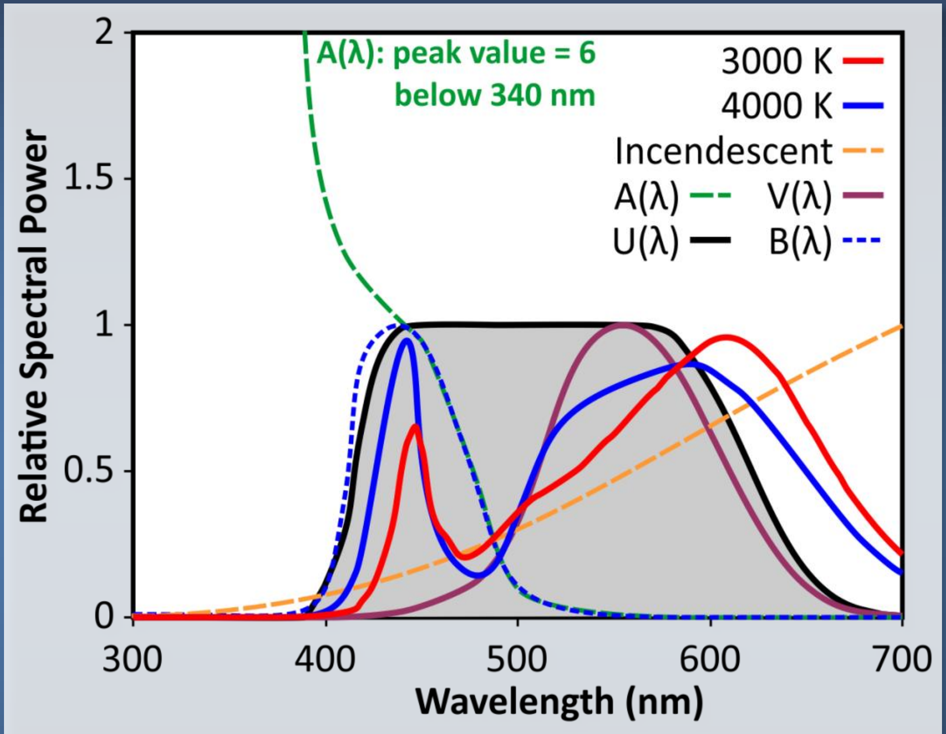
Blue light hazard (summary)

Spectrum matters …but it's not the biggest factor



Optics matters: Block or diffuse the source; eliminate or reduce *radiance*

Use cases matter: Most people exhibit photophobia

Special populations: newborns, aphakic lens replacement, actors

Glare

- Disability glare
  - Reduction in visibility caused by luminous veil due to scattered light in the eye
  - Well-understood quantitatively for decades (Fry 1954)
- Discomfort glare
  - Annoying or painful sensation when exposed to a bright light in the field of view
  - Understood more recently (Bullough et al. 2003, Bullough 2009, Bullough and Sweater Hickcox 2012)

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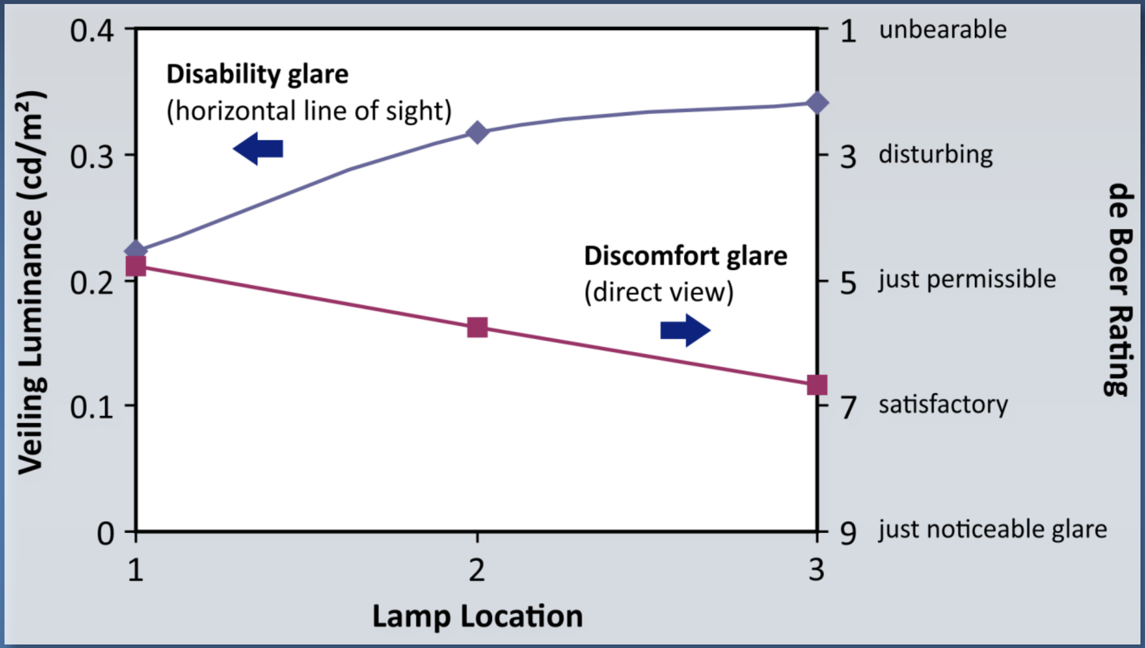
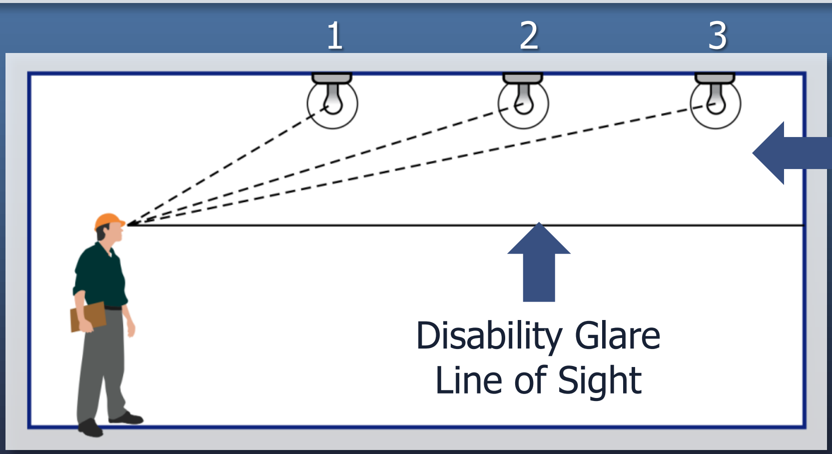
Glare

100-watt incandescent lamps





Discomfort Glare Lines of Sight

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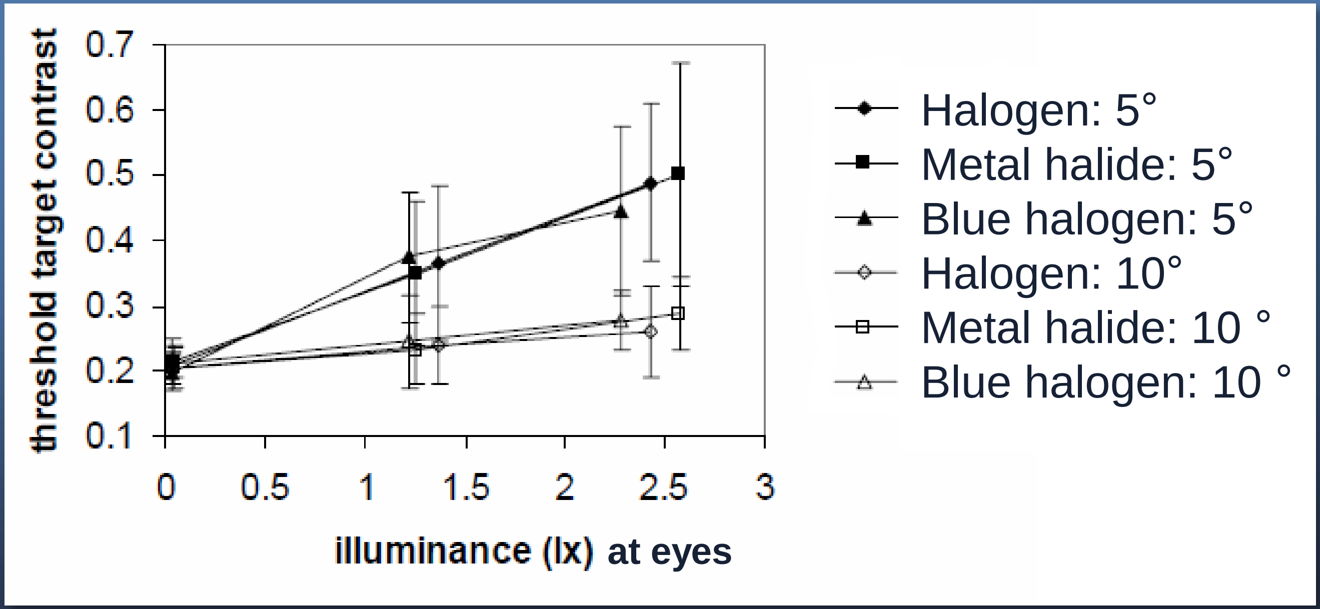
Disability glare

- Disability glare is primarily a function of photopic illuminance at the eyes and the angular distance between the source and the object of interest (Bullough et al. 2002, 2003)
- Different spectra do not differentially affect on-axis visual performance, acuity, contrast threshold, or reaction time



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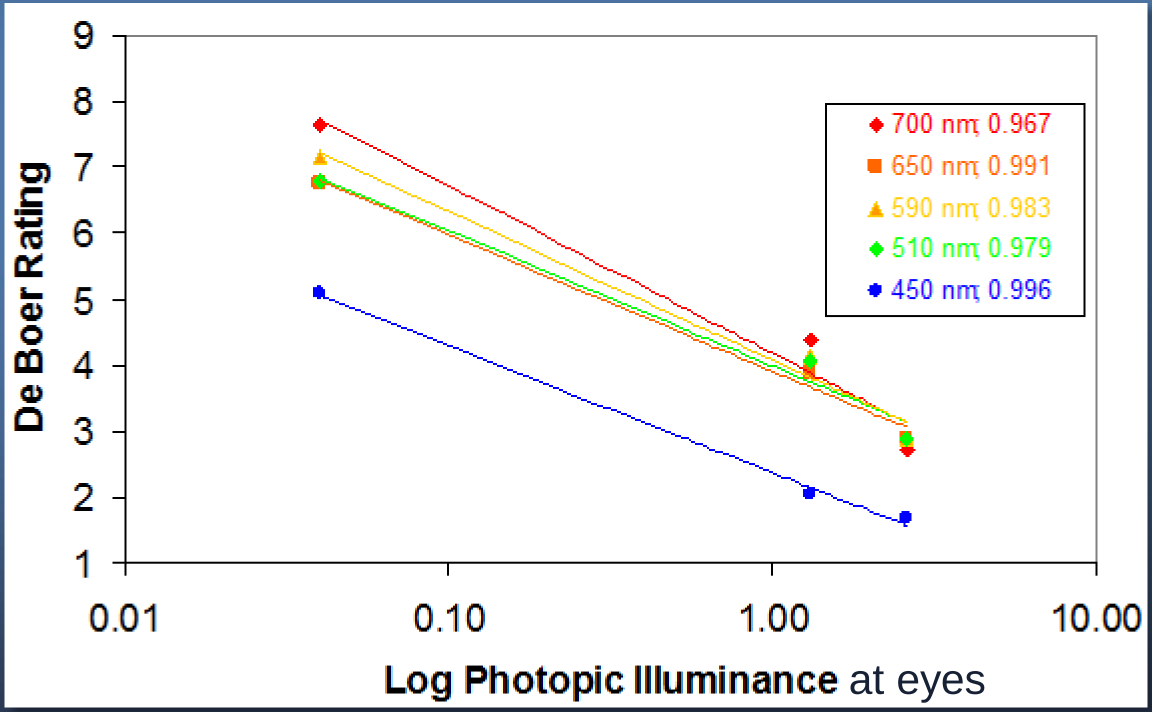
Discomfort glare

- Short wavelength increased discomfort glare for the same photopic illuminance at the eyes



9: Just noticeable
8:
7: Satisfactory
6:
5: Just acceptable
4:
3: Disturbing
2:
1: Unbearable

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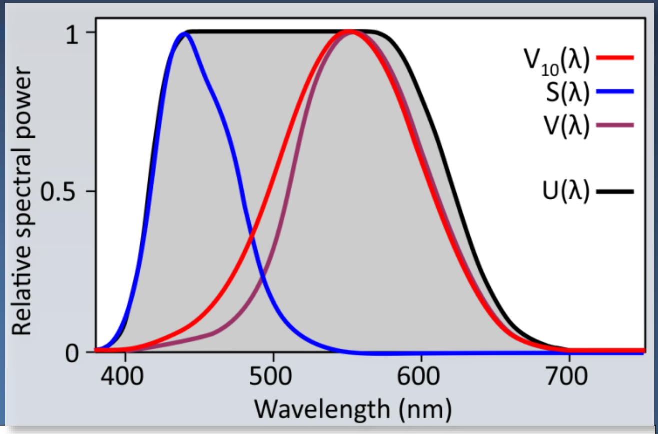
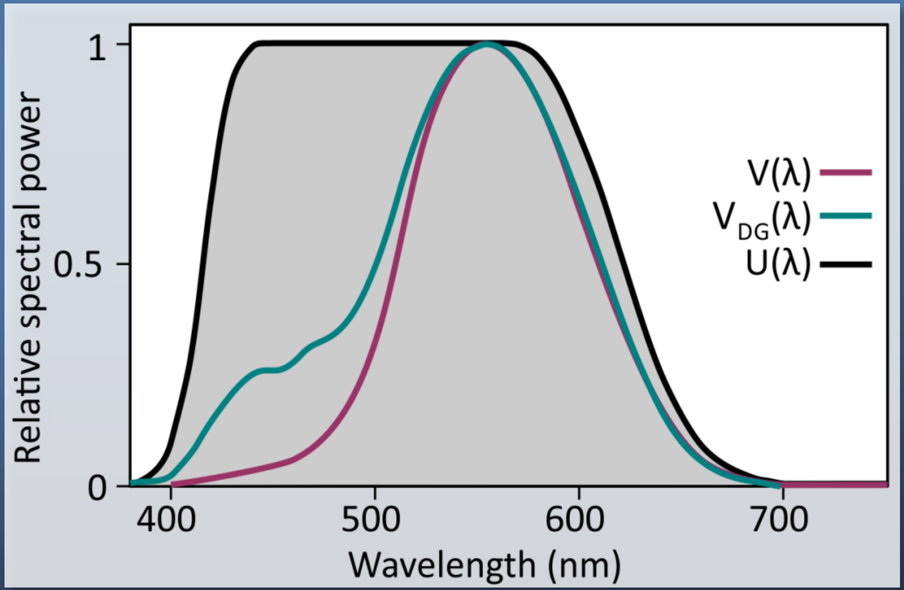
Spectral sensitivity of discomfort glare (DG)

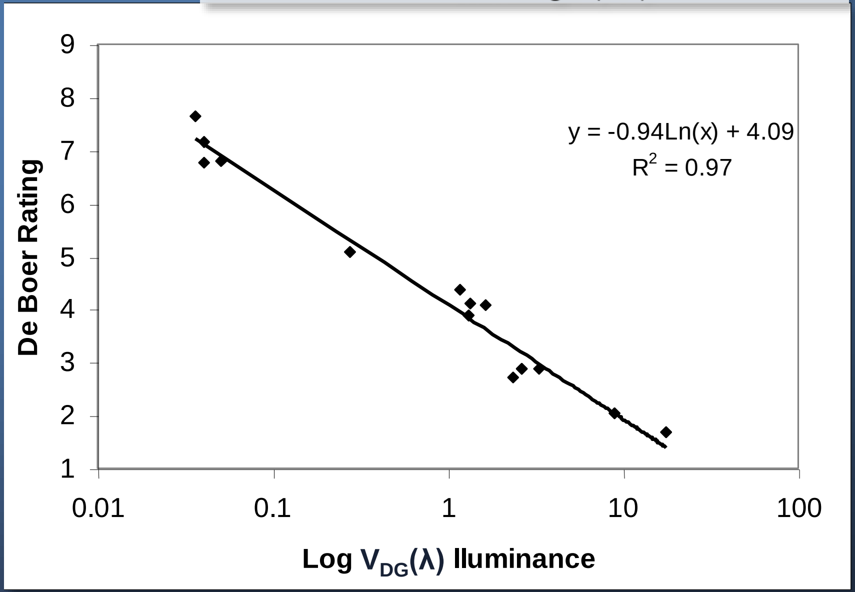
- A combination of $V_{10}(\lambda)$ and short-wavelength cone sensitivity $S(\lambda)$ was the best rectifying variable for discomfort ratings [$V_{DG}(\lambda)$]





$V_{DG}(\lambda) = V_{10}(\lambda) + kS(\lambda)$

$k = 0.19$



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Glare (summary)

Disability Glare		Discomfort Glare
✓✓✓	Photopic illuminance at the eye	✓✓✓
✓✓	Angle between glare source and line of sight	✓✓
NA	Luminance of the source (> 0.3°)	✓
NA	SPD	✓
NA	Psychological	✓

✓✓✓ Most important ✓✓ Very important ✓ Important NA Not applicable

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Part 2

Mariana G. Figueiro, PhD

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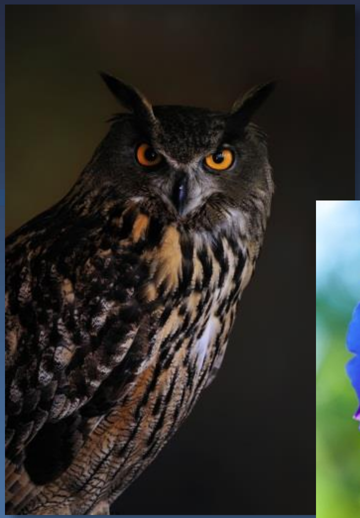
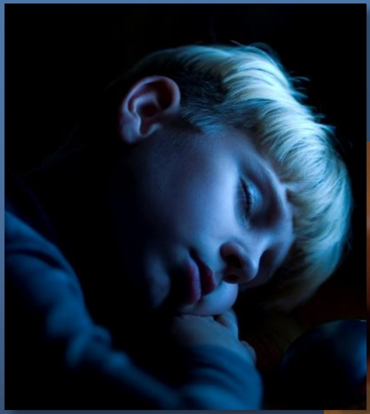
Circadian system

- Circadian rhythms are biological processes that display an endogenous (and entrainable) rhythm close to 24 h

circa = approximately; *dies* = day

- Circadian rhythms are generated and regulated by a biological clock in the brain
  - In humans, circadian rhythms free run with a period slightly greater than 24 h





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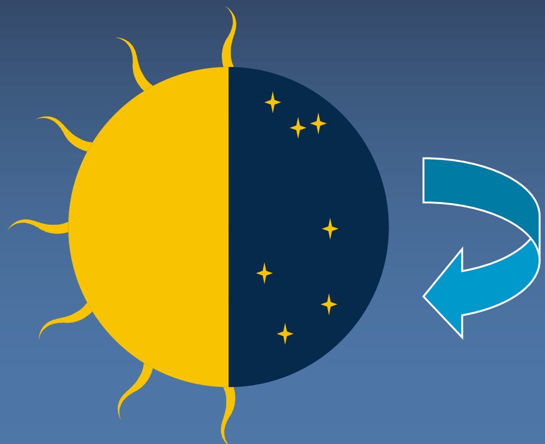
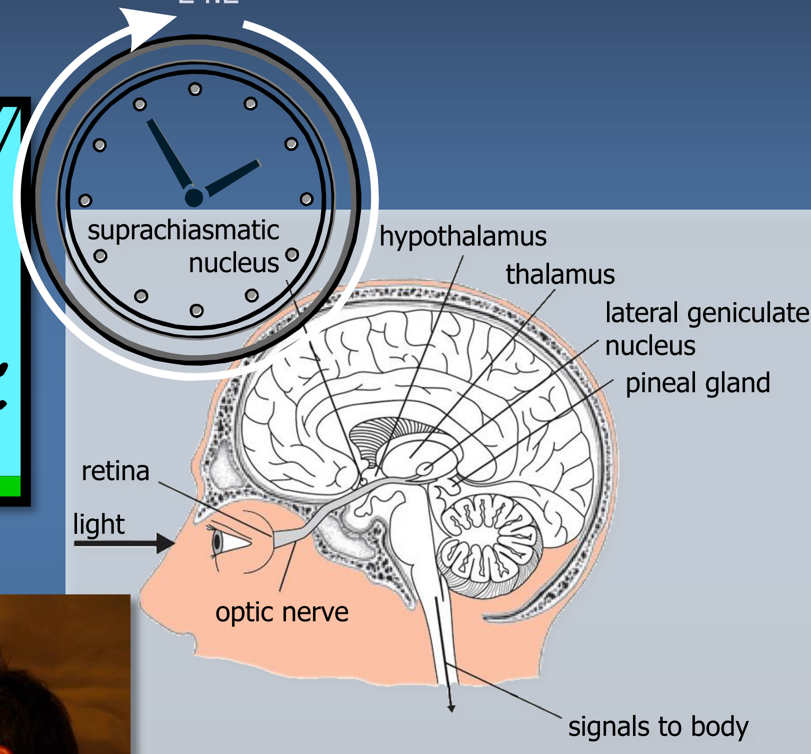
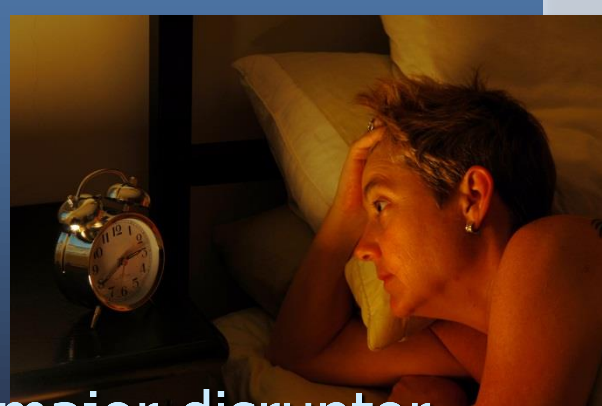
Light on the retinae is the primary synchronizer of circadian rhythms to local position on Earth



The natural, 24-hour, light-dark cycle



Adapted from National Library of Medicine image, 2007 (public domain)



…also the major disruptor

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Implications of circadian disruption

- Circadian disruption has been associated with:
  - Poor sleep, poor performance and high stress

    Eismann, E. A., Lush, E., & Sephton, S. E. (2010). Circadian effects in cancer-relevant psychoneuroendocrine and immune pathways. *Psychoneuroendocrinology,* 35(7), 963-976.

    Gumenyuk, V., Howard, R., Roth, T., Korzyukov, O., Drake, C.L. (2014) Sleep loss, circadian mismatch, and abnormalities in reorienting of attention in night workers with shift work disorder. Sleep. March 1; 37(3): 545–556.
  - Increased anxiety and depression

    Du-Quiton, J., Wood, P. A., Burch, J. B., Grutsch, J. F., Gupta, D., Tyer, K., . . . Reynolds, J. L. (2010). Actigraphic assessment of daily sleep–activity pattern abnormalities reflects self-assessed depression and anxiety in outpatients with advanced non-small cell lung cancer. *Psycho-Oncology*, 19(2), 180-189.
  - Increased smoking

    Kageyama, T., Kobayashi, T., Nishikido, N., Oga, J., & Kawashima, M. (2005). Associations of sleep problems and recent life events with smoking behaviors among female staff nurses in Japanese hospitals. *Industrial Health*, 43(1), 133-141.
  - Cardiovascular disease

    Young, M. E., & Bray, M. S. (2007). Potential role for peripheral circadian clock dyssynchrony in the pathogenesis of cardiovascular dysfunction. *Sleep Medicine*, 8(6), 656-667.

    Maemura, K., Takeda, N., & Nagai, R. (2007). Circadian rhythms in the CNS and peripheral clock disorders: role of the biological clock in cardiovascular diseases. *Journal of Pharmacological Sciences*, 103(2), 134-138.
  - Type 2 diabetes

    Kreier, F., Kalsbeek, A., Sauerwein, H. P., Fliers, E., Romijn, J. A., & Buijs, R. M. (2007). "Diabetes of the elderly" and type 2 diabetes in younger patients: Possible role of the biological clock. *Experimental Gerontology*, 42(1), 22-27.
  - Higher incidence of breast cancer

    Schernhammer, E. S., Laden, F., Speizer, F. E., Willett, W. C., Hunter, D. J., Kawachi, I., & Colditz, G. A. (2001). Rotating night shifts and risk of breast cancer in women participating in the Nurses' Health Study. *Journal of the National Cancer Institute*, 93(20), 1563-1568.

    Hansen, J. (2006). Risk of breast cancer after night-and shift work: current evidence and ongoing studies in Denmark. *Cancer Causes & Control*, 17(4), 531-537.

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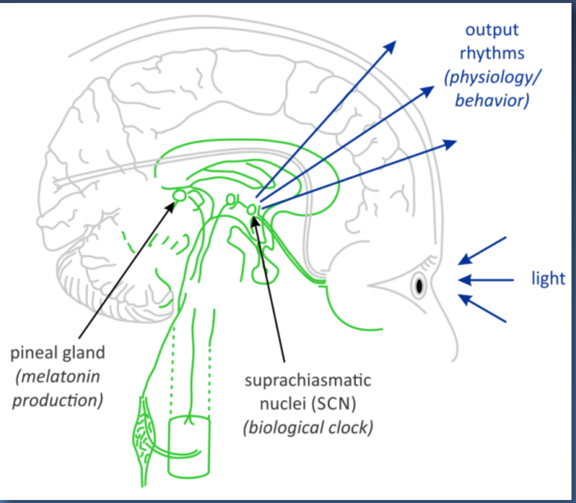
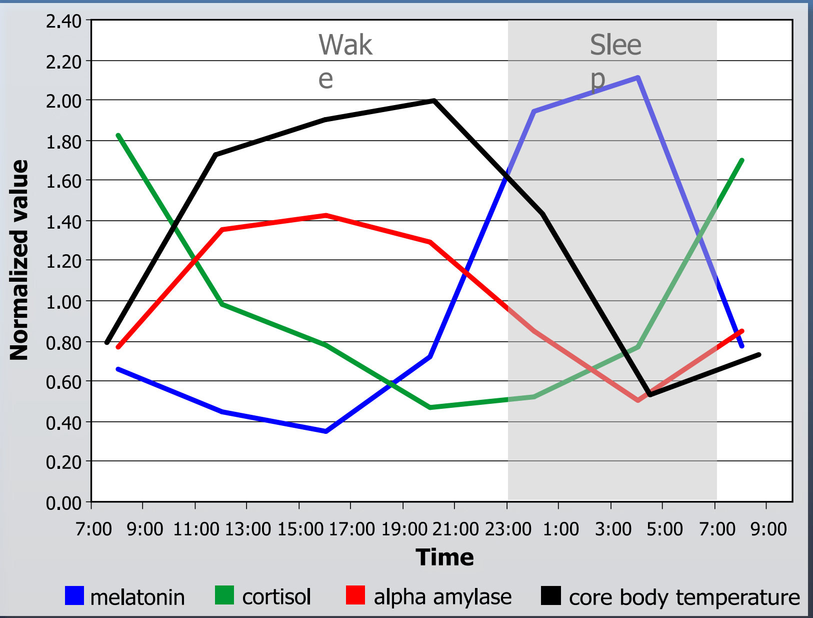
Light can also exert acute effects on humans

- Melatonin is a hormone produced at night and in darkness
  - Timing messenger for the body
  - Shown to have oncostatic effect in animal studies
- Light can suppress nocturnal melatonin production or phase shift the evening timing of melatonin onset
  - Short wavelength light (peak close to 460 nm) is maximally effective at suppressing melatonin





Light at night (LAN) and health

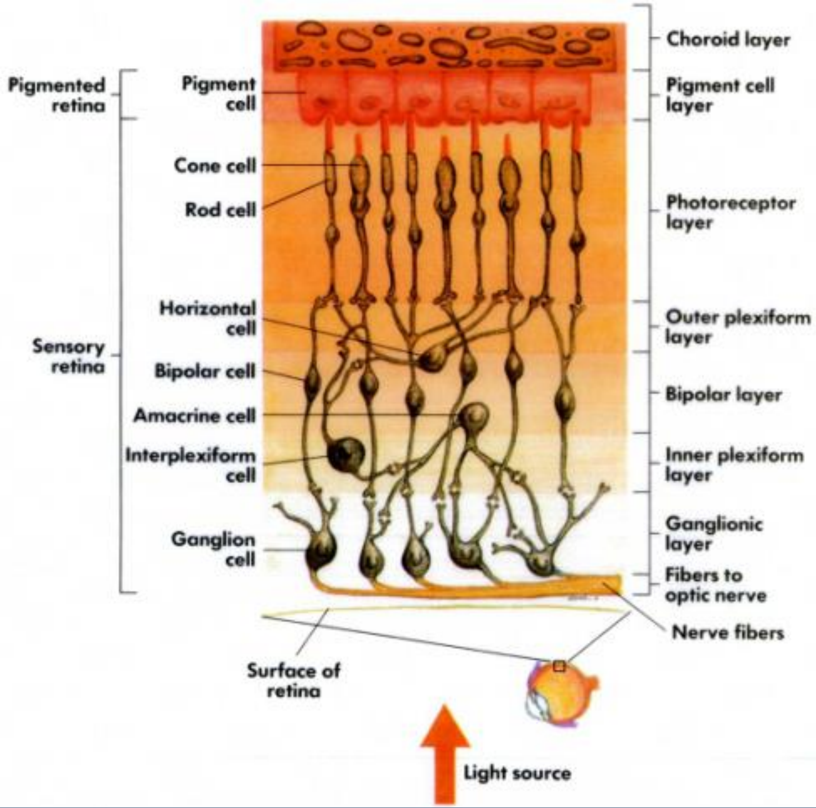
- "Melatonin Hypothesis"
  - Suppression of melatonin by LAN and electromagnetic fields (EMFs) was hypothesized to increase production of estrogens in the ovaries, which in turn would stimulate the turnover of breast epithelial stem cells, thereby increasing the likelihood of cancer

    Stevens R. G. (1987). Electric power use and breast cancer: A hypothesis. *American Journal of Epidemiology*, 125, 556-561.

- "Circadian Disruption" Hypothesis
  - Disruption of the circadian system by LAN has been associated with
    - Breast cancer risk
    - Diabetes and obesity
    - Cardiovascular disease

Circadian phototransduction

- Intrinsically photosensitive retinal ganglion cells – ipRGCs (Berson et al. 2002)
  - Located in the ganglion cell layer
  - Peak spectral sensitivity at about 480-484 nm
    - Melanopsin is believed to be the photopigment in the ipRGCs
  - Receives and sends "processed information," including spectral opponency formed at bipolar cells, to the biological clock



Berson, D., Dunn, F., Takao, M. (2002). Phototransduction by retinal ganglion cells that set the circadian clock. *Science*, 295, 1070-1073.c

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All 5 photoreceptors participate in circadian phototransduction

Published in final edited form as:
Nature. 2003 July 3; 424(6944): 76–81. doi:10.1038/nature01761.

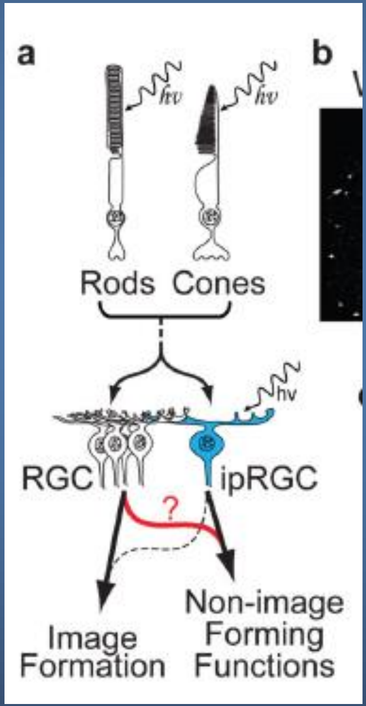
Melanopsin and rod–cone photoreceptive systems account for all major accessory visual functions in mice

S. Hattar[*], R. J. Lucas[†], N. Mrosovsky[‡], S. Thompson[†], R. H. Douglas[§], M. W. Hankins[†], J. Lem[||], M. Biel[¶], F. Hofmann[#], R. G. Foster[†], and K.-W. Yau[*]
[*]Howard Hughes Medical Institute and Department of Neuroscience, Johns Hopkins University School of Medicine, Baltimore, Maryland 21205, USA

But, ipRCGS are needed to transduce the signals from rods and cones, but melanopsin knockout mice can still entrain to a light pulse

Melanopsin cells are the principal conduits for rod/cone input to non-image forming vision

Ali D. Güler[1,*], Jennifer L. Ecker[1,*], Gurprit S. Lall[2,*], Shafiqul Haq[3], Cara M. Altimus[1], Hsi-Wen Liao[3], Alun R. Barnard[2], Hugh Cahill[3], Tudor C. Badea[4], Haiqing Zhao[1], Mark W. Hankins[5], David M. Berson[6], Robert J. Lucas[2,†], King-Wai Yau[3], and Samer Hattar[1,†]
[1] Department of Biology, Johns Hopkins University, Baltimore, MD 21218, USA



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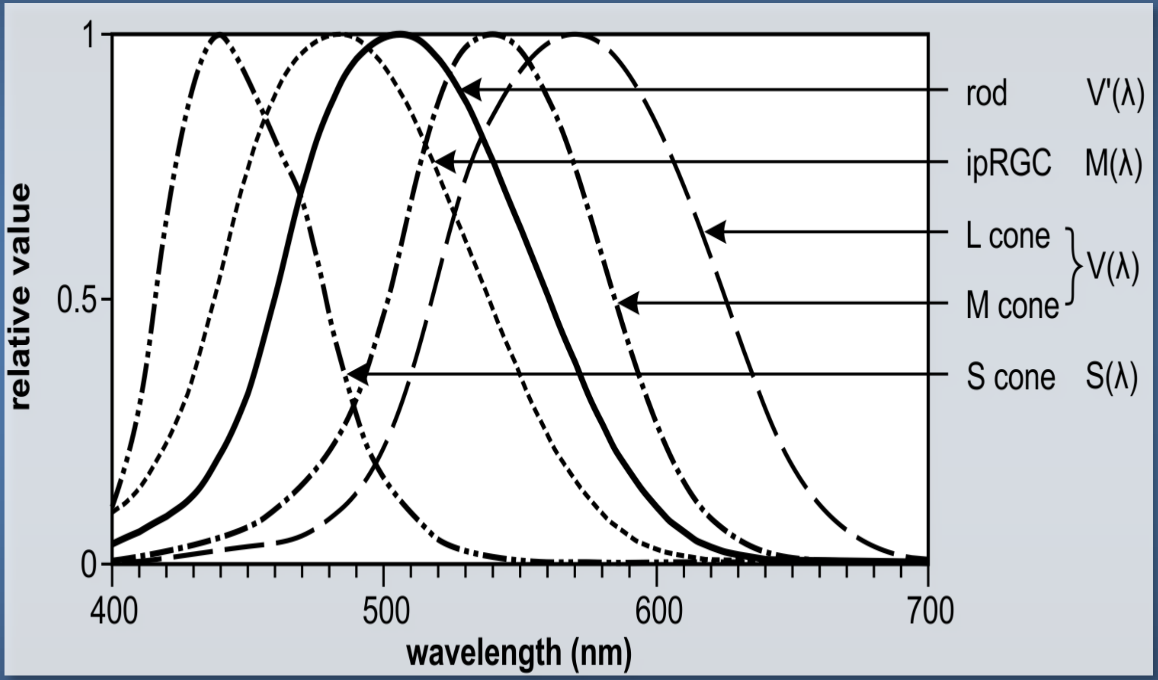
All 5 photoreceptors are needed for circadian phototransduction



But how are they combined to respond to light for the circadian system?

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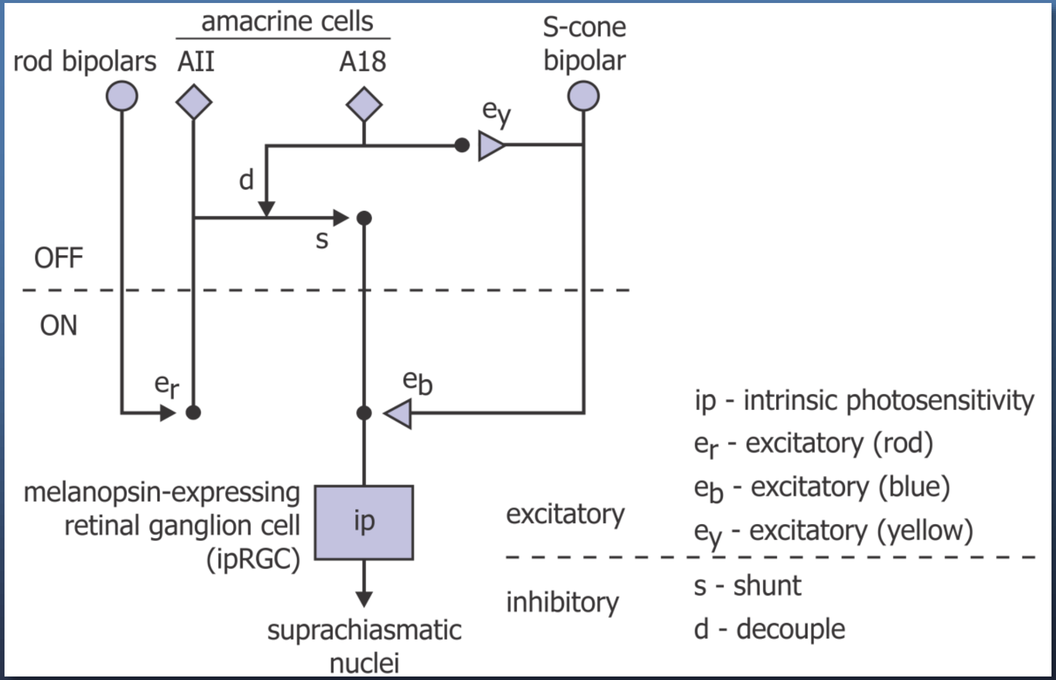
Model of circadian phototransduction

- Constrained by known photopigments and neuroanatomy and neurophysiology of the human retina
  - Includes ipRGCs and classical photoreceptors
  - Includes subadditivity resulting from spectral opponent input to the ipRCG from b-y color channel (formed at the bipolar level)



Rea et al., 2005

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Model of circadian phototransduction

$$CL_A = \begin{cases} 1548\left[\int Mc_\lambda E_\lambda d\lambda + \left(a_{b-y}\left(\int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda\right) - a_{rod}\left(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{RodSat}}\right)\right)\right] & \text{if } \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda > 0 \\ 1548 \int Mc_\lambda E_\lambda d\lambda & \text{if } \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda \leq 0 \end{cases}$$

CL_A: Circadian light. The constant, 1548, sets the normalization of CL_A so that 2856 K blackbody radiation at 1000 lux has a CL_A value of 1000.

E_λ: light source spectral irradiance distribution

Mc_λ: melanopsin (corrected for crystalline lens transmittance)

S_λ: S-cone fundamental

mp_λ: macular pigment transmittance

V_λ: Photopic luminous efficiency function

V'_λ: Scotopic luminous efficiency function

RodSat: Half-saturation constant for bleaching rods = 6.5 W/m²

k = 0.2616

a_{b-y} = 0.700

a_{rod} = 3.300

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Circadian stimulus (CS)

- Transfer function between the light stimulus (CL_A) and circadian response (nocturnal melatonin suppression)

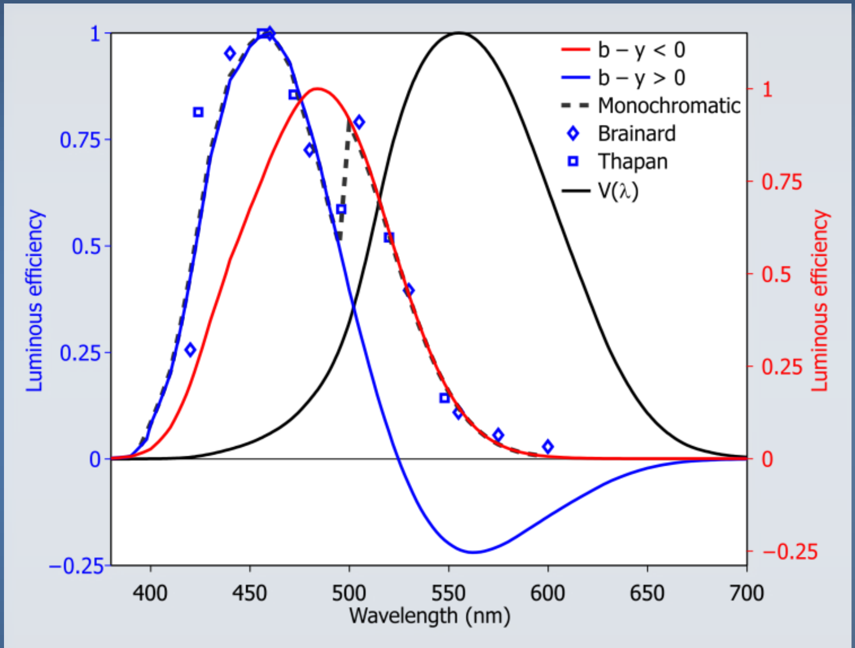
$$CS = 0.7 - \frac{0.7}{1 + \left(\frac{CL_A}{355.7}\right)^{1.1026}}$$

Notes

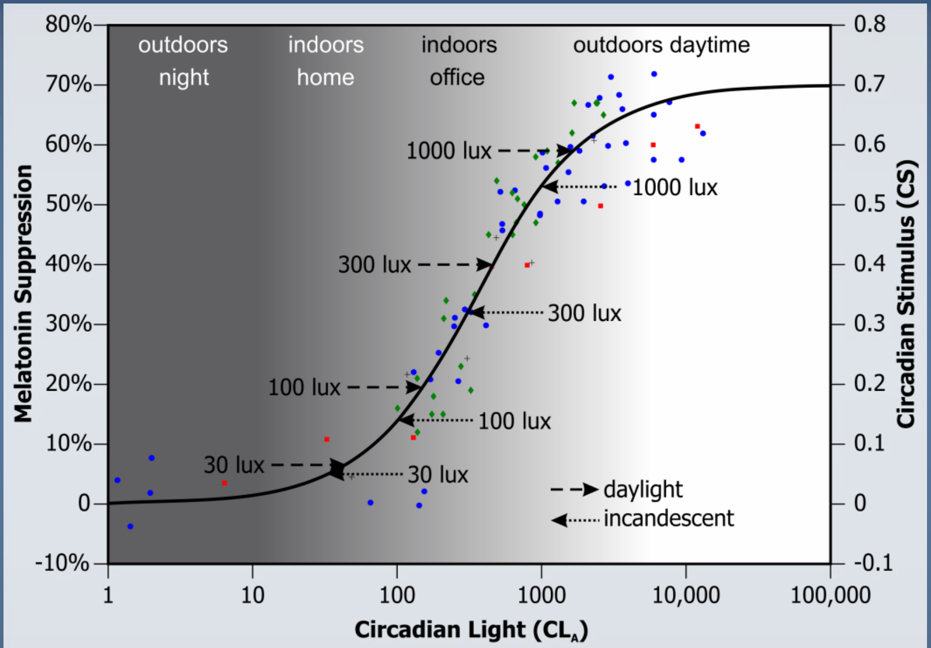
1. Pupil diameter = 2.3 mm
2. Three methods of calculating suppression

Circadian light (CL_A) and circadian stimulus (CS)

Spectral sensitivity



Absolute sensitivity



Rea, M. S., Figueiro, M. G., Bullough, J. D., & Bierman, A. (2005). A model of phototransduction by the human circadian system. *Brain Research Reviews,* 50(2), 213-228.

Rea, M. S., Figueiro, M. G., Bierman, A., & Hamner, R. (2012). Modelling the spectral sensitivity of the human circadian system. *Lighting Research and Technology,* 44(4), 386-396.

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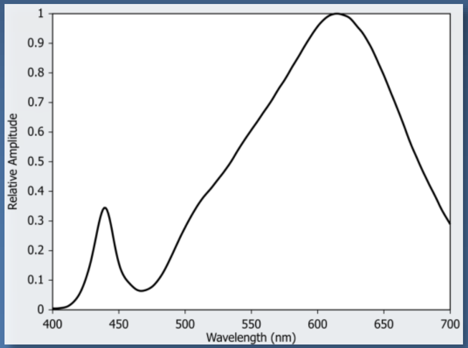
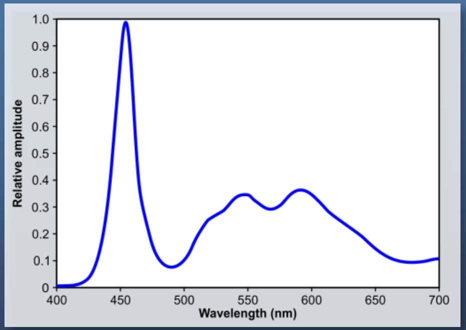
Validation with practical sources

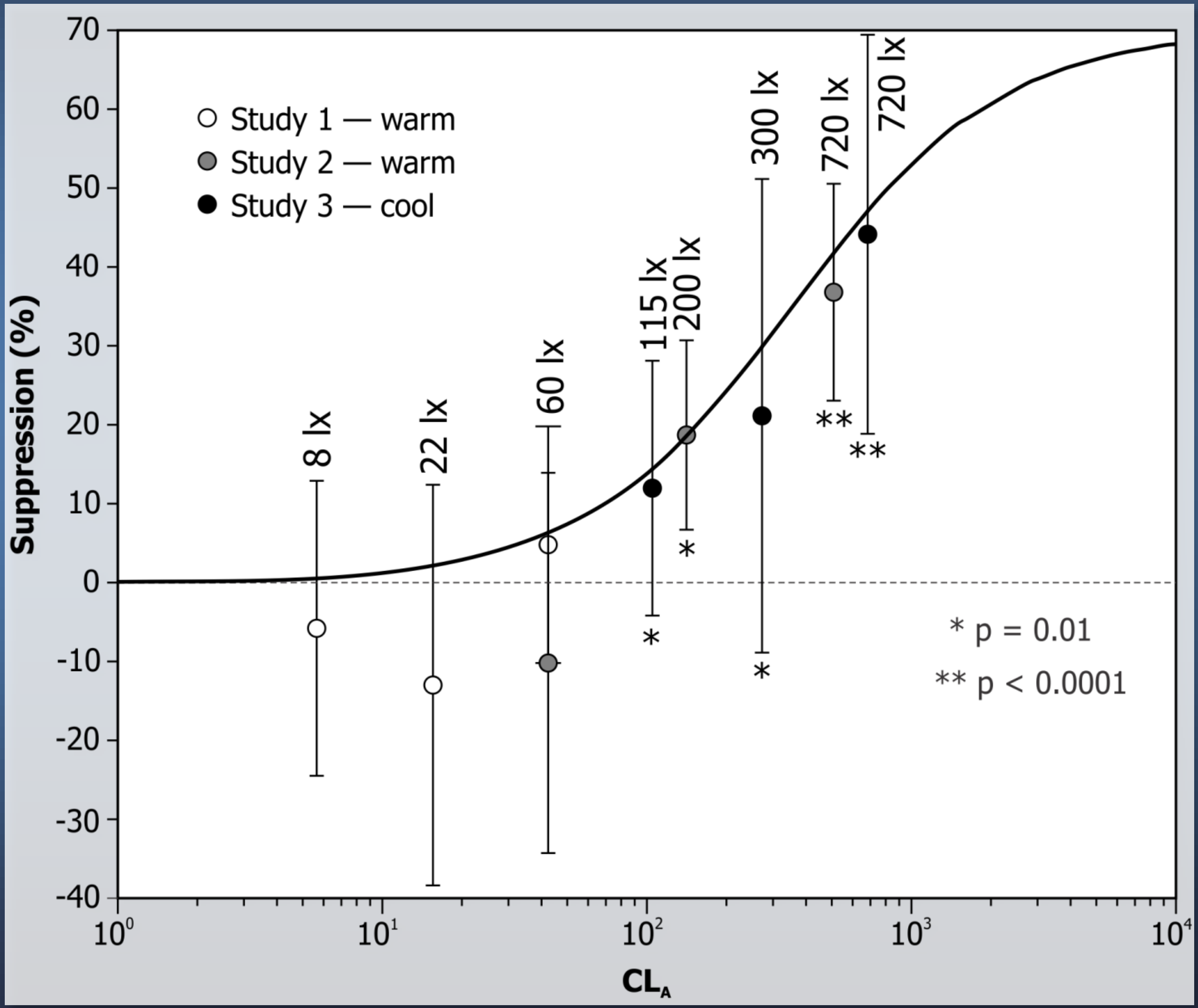
Rea MS, Figueiro MG (2013) A Working Threshold for Acute Nocturnal Melatonin Suppression from "White" Light Sources used in Architectural Applications. *J Carcinogene Mutagene* 4: 150 doi: 10.4172/2157-2518.1000150

"warm" white light source
CCT = 2670 K



"cool" white light source
CCT = 6400 K





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Circadian stimulus (CS): Metric for quantifying effectiveness of light sources for activating the circadian system

Select Source SPD

CIE D65

(Click cell above for pull-down menu)

Illuminance (lux)

1000

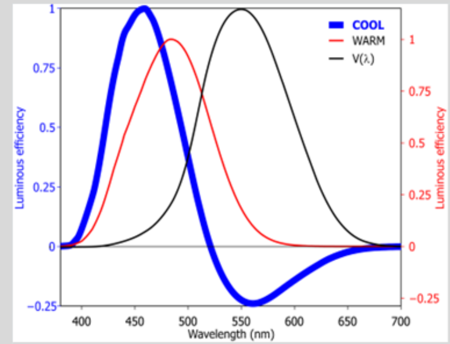
(Enter illuminance in cell above)

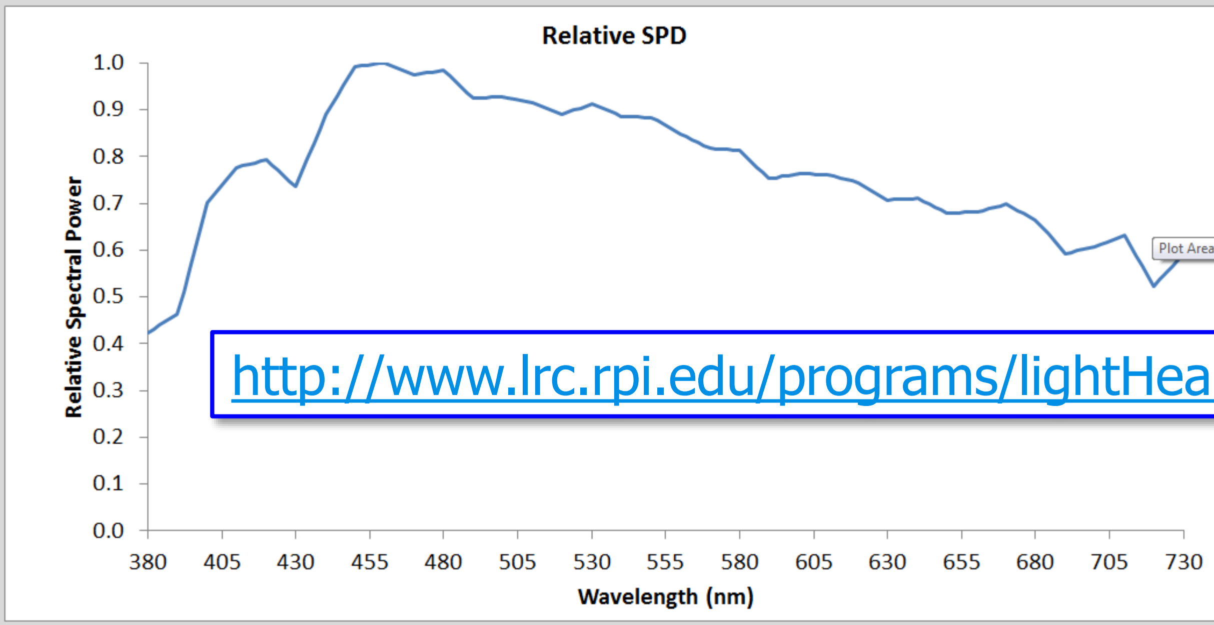
Circadian Light (CL_A)

1696 Circadian lux

Circadian Stimulus (CS)

0.594





http://www.lrc.rpi.edu/programs/lightHealth/index.asp

User SPD

Wavelength (nm)	Value
3.80E+02	0.09795
3.82E+02	0.10227
3.84E+02	0.10672
3.86E+02	0.1113
3.88E+02	0.11601
3.90E+02	0.12085
3.92E+02	0.12583
3.94E+02	0.13094
3.96E+02	0.13618
3.98E+02	0.14156
4.00E+02	0.14708
4.02E+02	0.15274
4.04E+02	0.15853
4.06E+02	0.16446
4.08E+02	0.17054
4.16E+02	0.19624
4.18E+02	0.20303
4.20E+02	0.20995
4.22E+02	0.21702
4.24E+02	0.22423
4.26E+02	0.23158
4.28E+02	0.23907
4.30E+02	0.24671

Sponsor: Light and Health Alliance
(Acuity Brands, Cree, GE Lighting, Ketra Inc., OSRAM Sylvania, Philips Lighting, Sharp, USAI Lighting)

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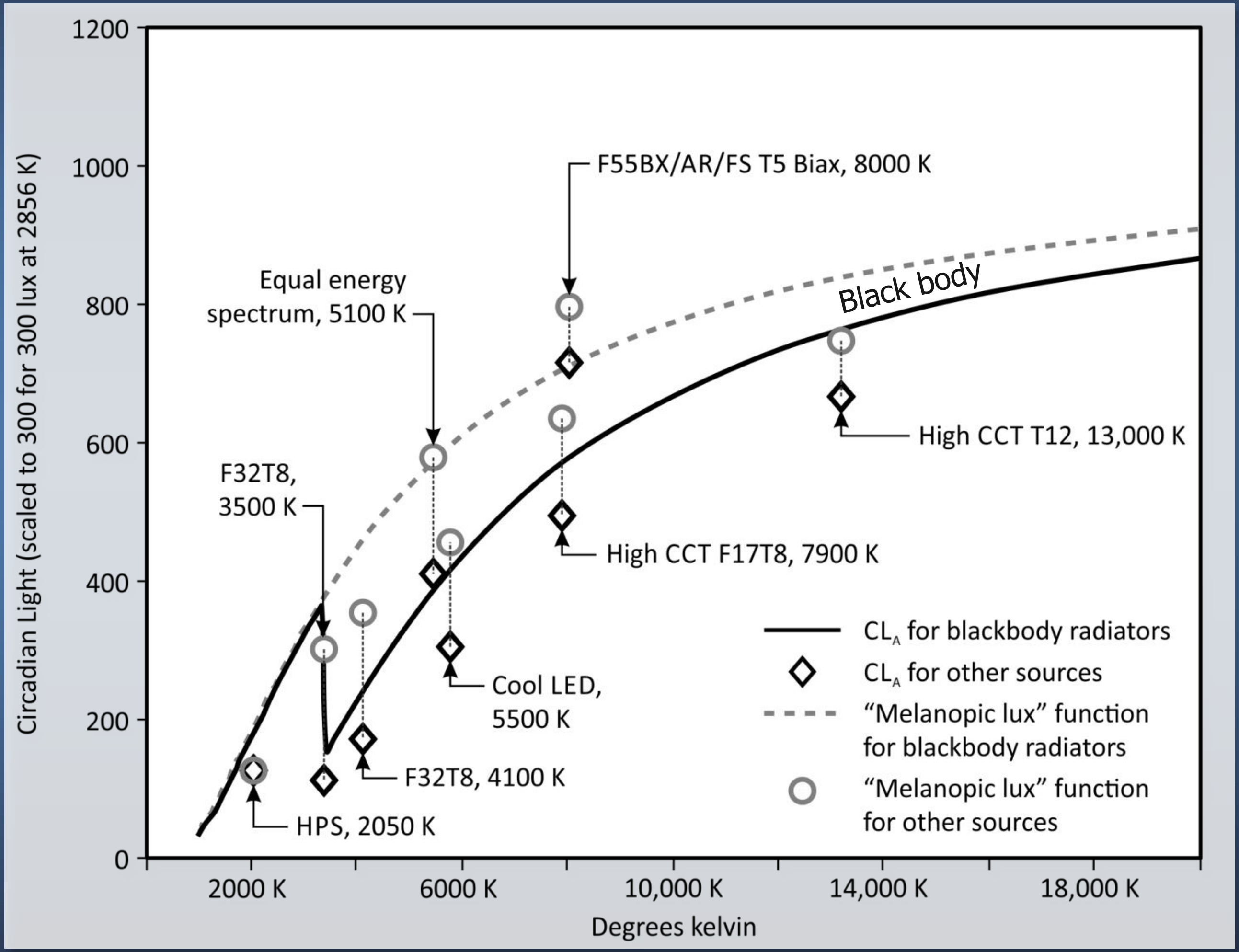
Correlated color temperature (CCT) and melatonin suppression



Rea and Figueiro. 2016. Light as a circadian stimulus for architectural lighting. *Lighting Research & Technology.* Doi 10.1177/1477153516682368

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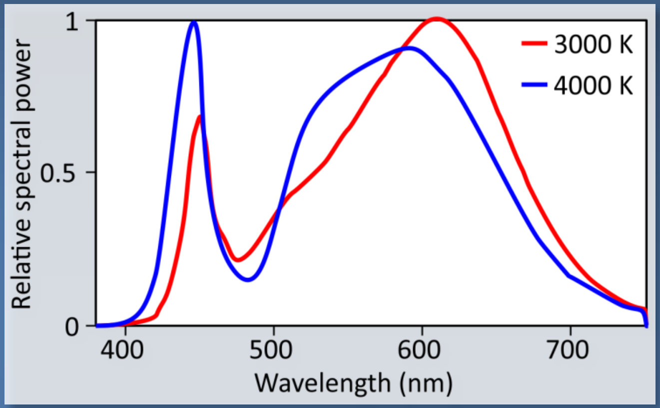
Circadian disruption and melatonin suppression Using circadian stimulus

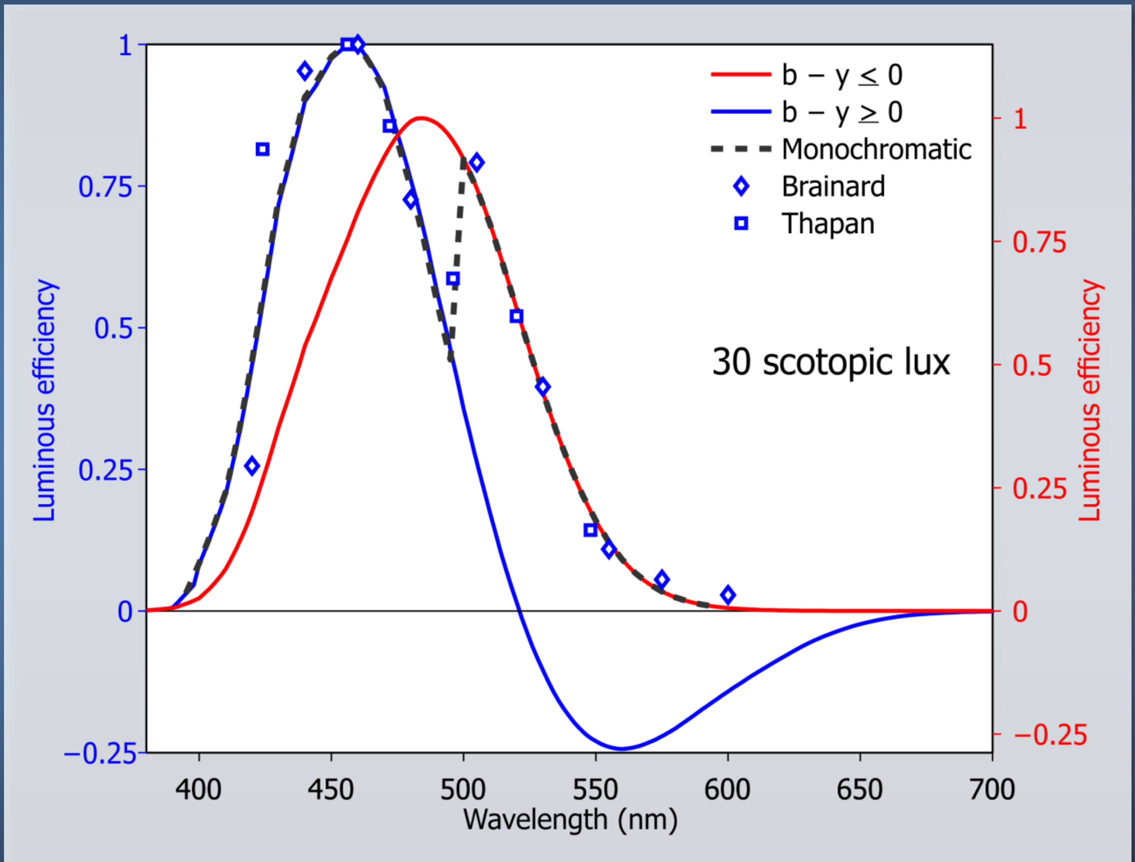
Spectral power distribution



LED

	3000 K	4000 K
lux	21.3	19.2
CL_A	21.9	10.8

4000 K *less effective* stimulus than 3000 K



Spectral Sensitivity

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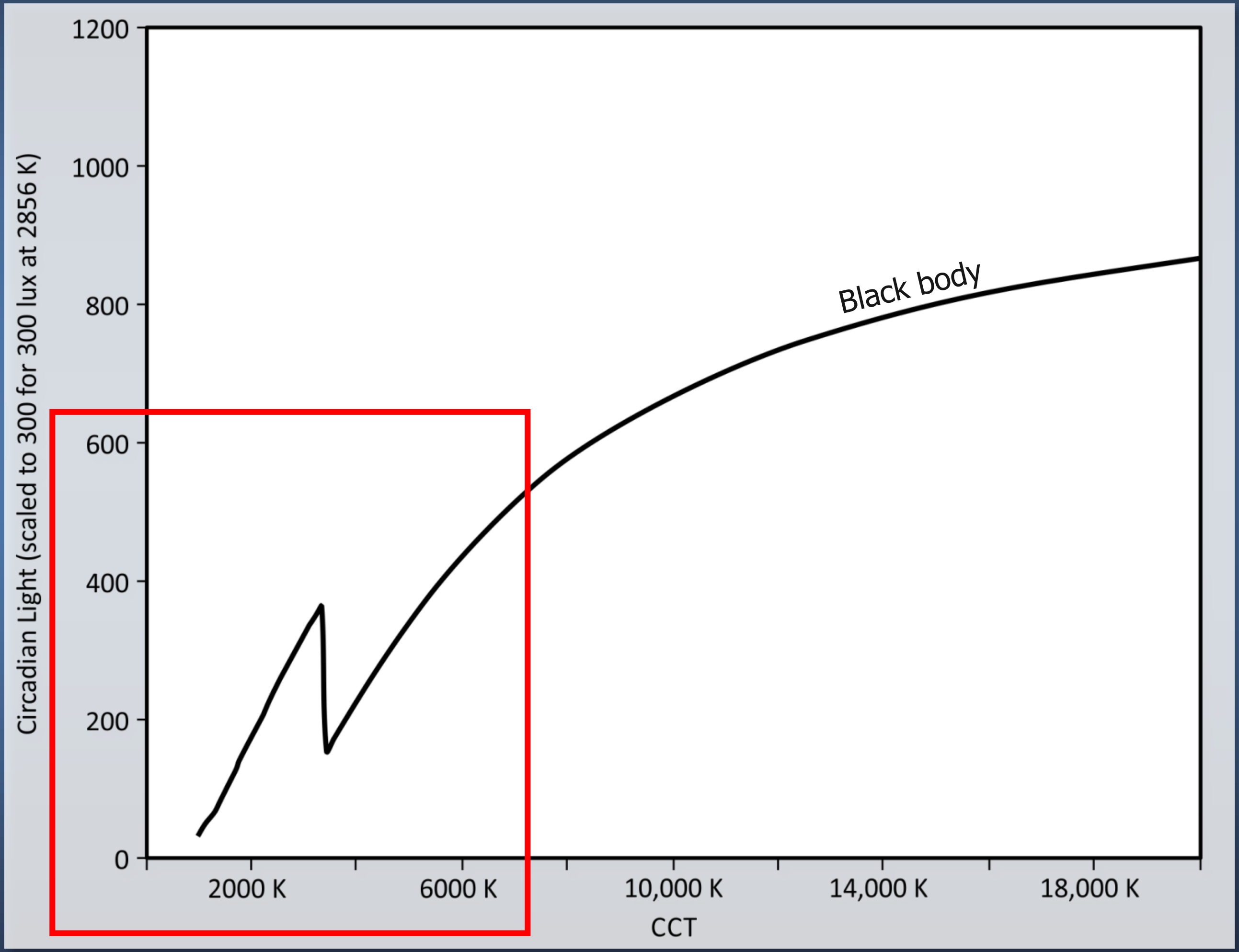
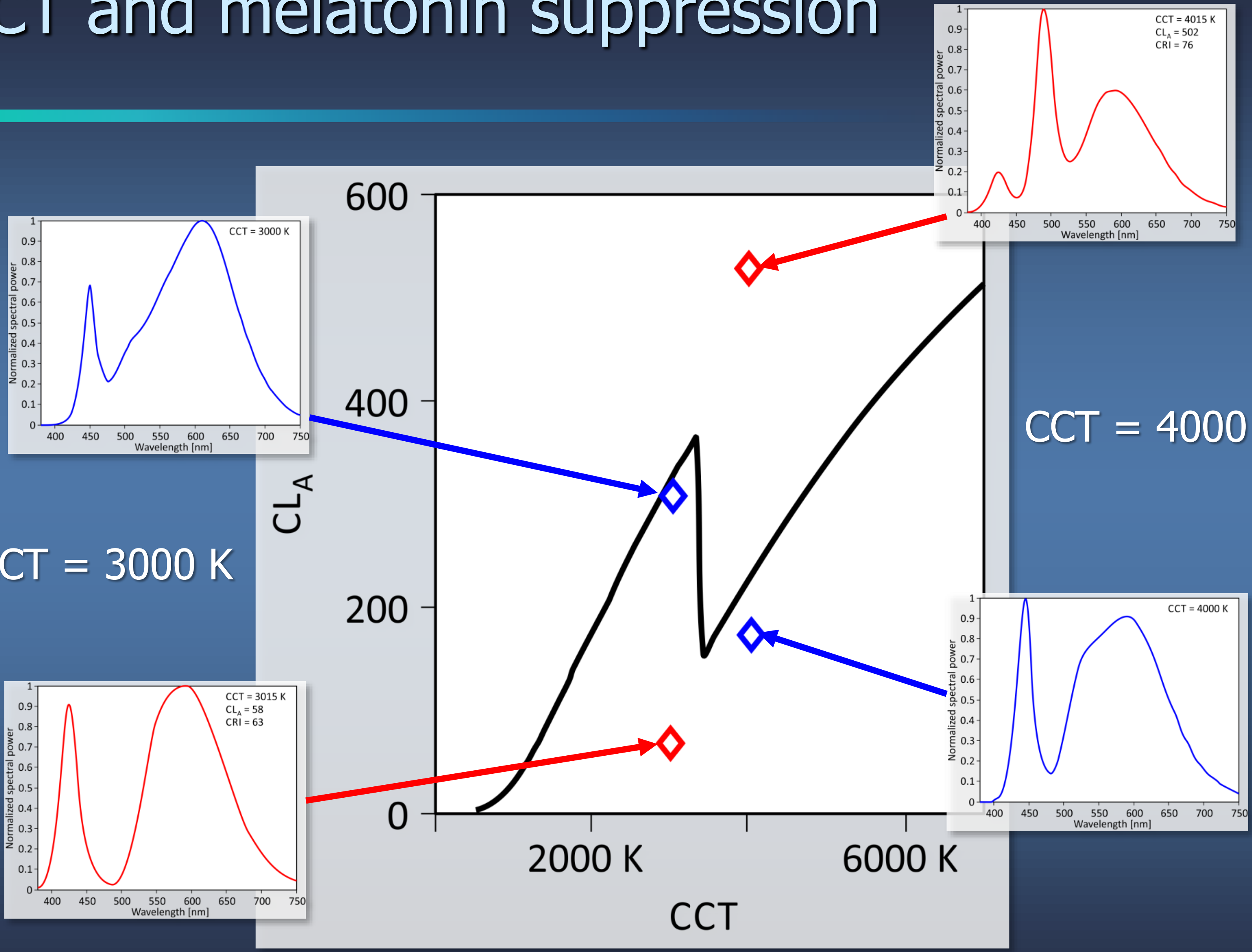
CCT and melatonin suppression



CCT and melatonin suppression



CCT = 4000 K

CCT = 3000 K

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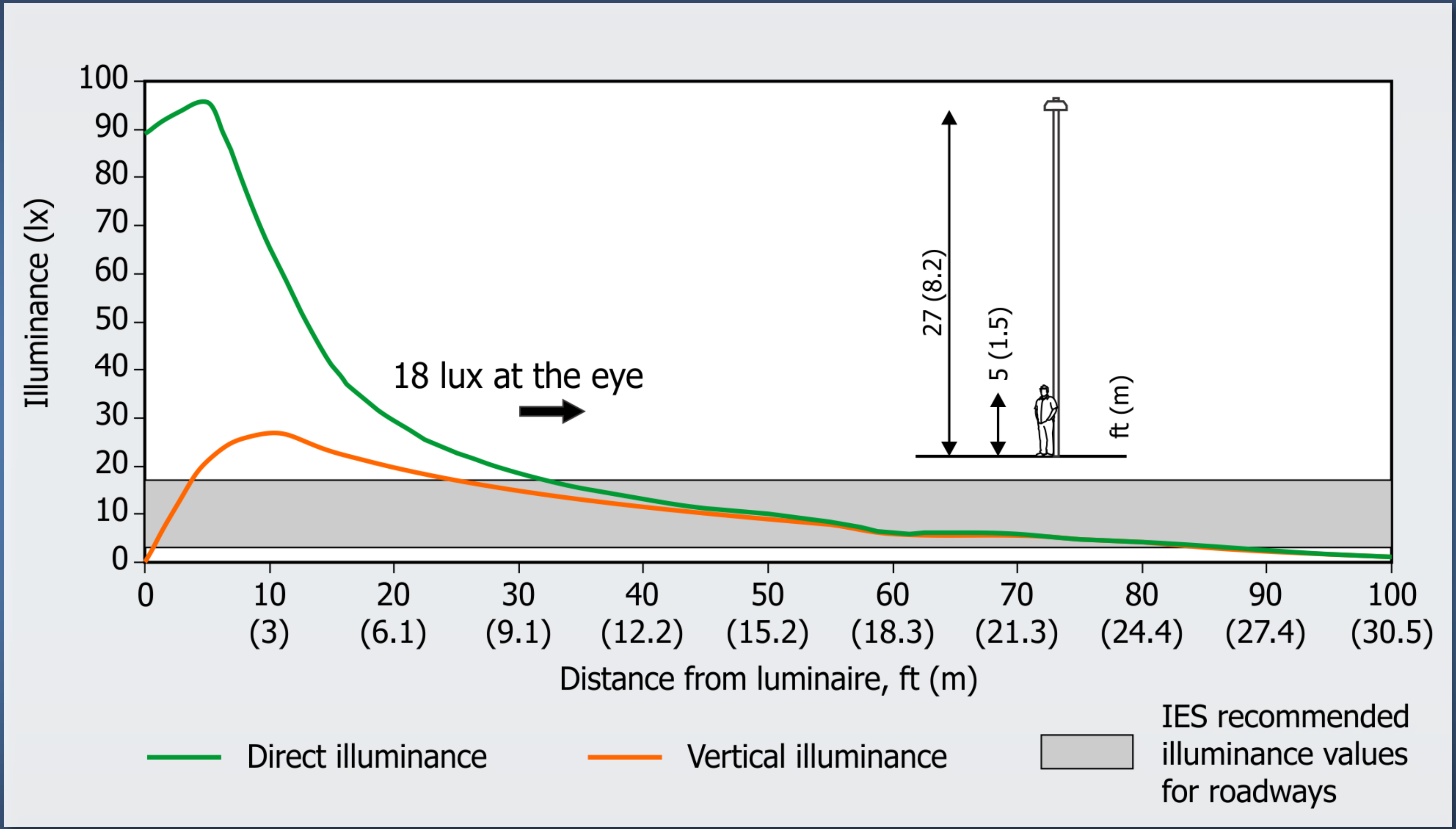
IES recommended levels: Amount only



Rea et al. 2010 (rev. 2012). The potential of outdoor lighting for stimulating the human circadian system. *Alliance for Solid-State Illumination Systems and Technologies (ASSIST).* Troy, NY.

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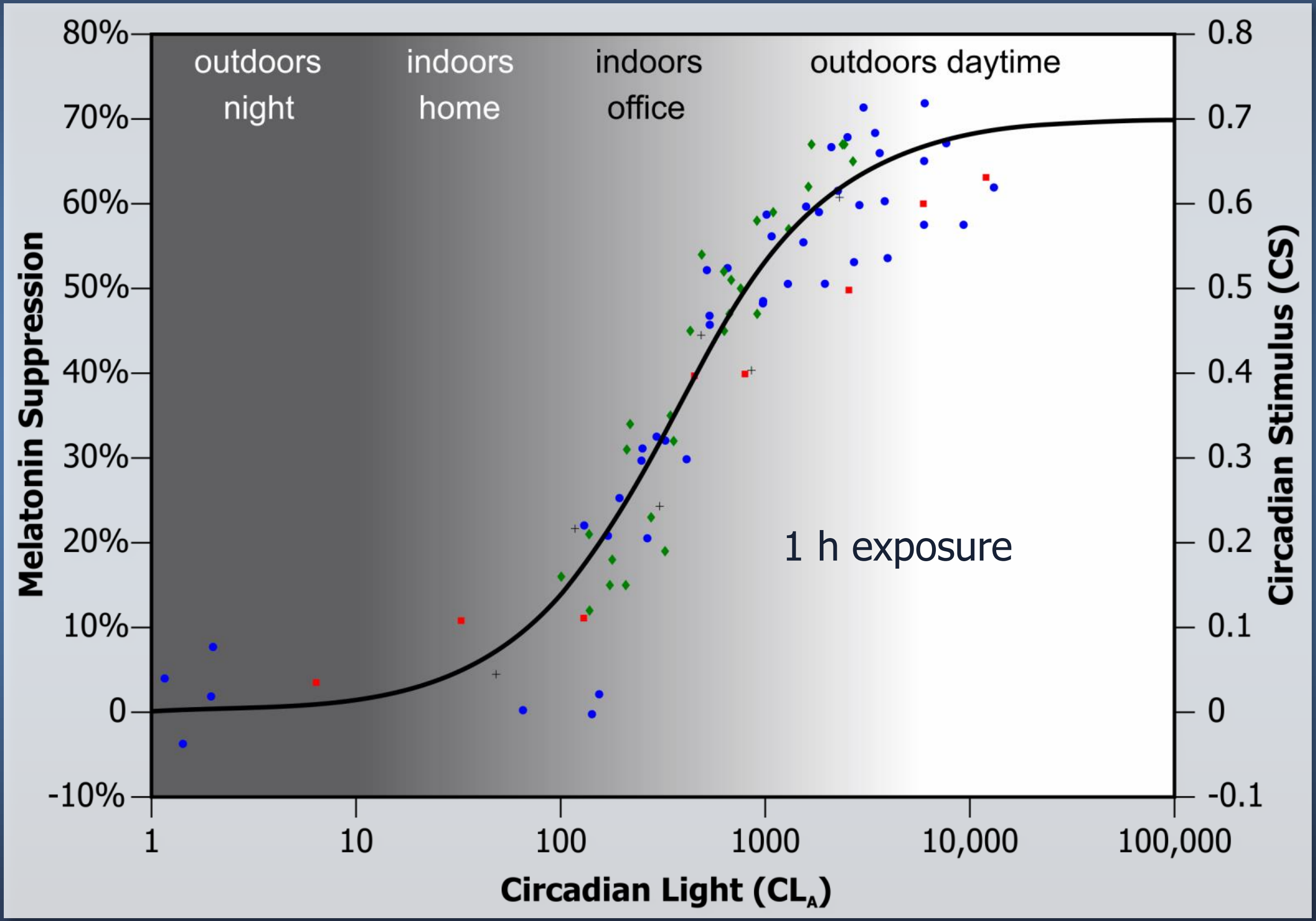
Circadian disruption and melatonin suppression Using circadian stimulus



Absolute Sensitivity

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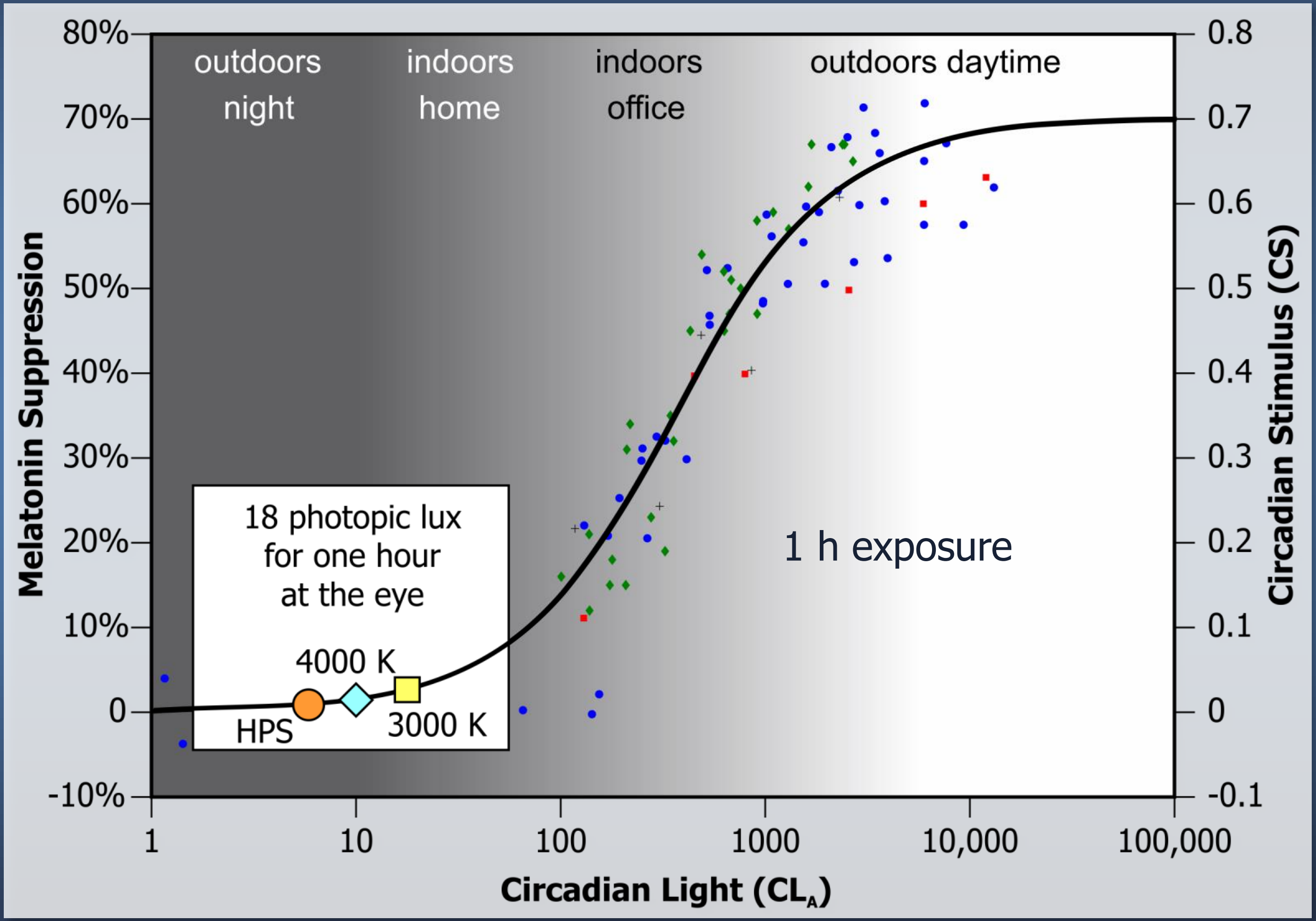
Circadian disruption and melatonin suppression Using circadian stimulus



Absolute Sensitivity

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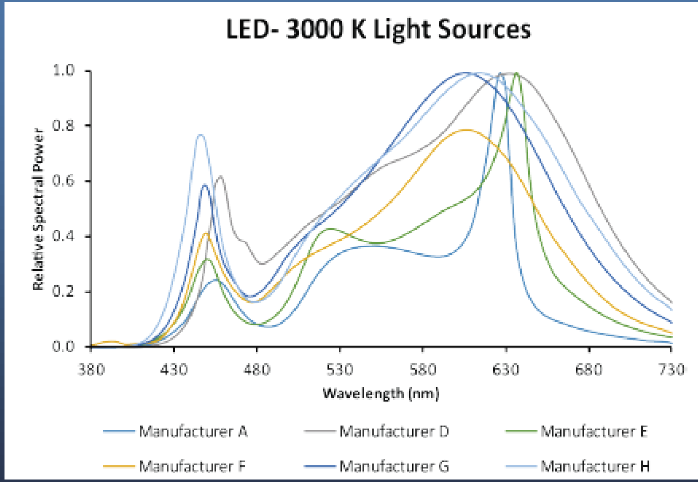
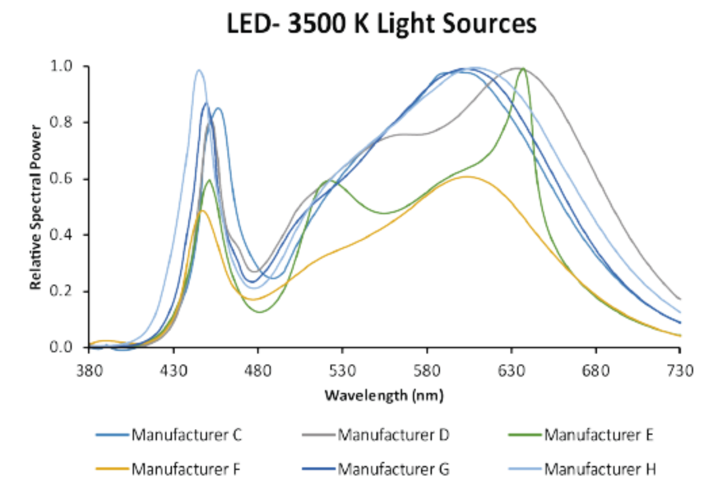
CCT and melatonin suppression
Indoor environments

Horizontal Illuminance (lux)	Manufacturer A	D	E	F	G	H
300	0.23	0.26	0.24	0.24	0.23	0.12
325	0.25	0.27	0.25	0.25	0.25	0.13
350	0.26	0.29	0.26	0.27	0.26	0.14
375	0.27	**0.30**	0.28	0.28	0.27	0.14
400	0.29	**0.31**	0.29	0.29	0.28	0.15
425	**0.30**	**0.33**	**0.30**	**0.30**	**0.30**	0.16
450	**0.31**	**0.34**	**0.31**	**0.31**	**0.31**	0.17
475	**0.32**	**0.35**	**0.32**	**0.32**	**0.32**	0.18
500	**0.33**	**0.36**	**0.33**	**0.33**	**0.33**	0.19

Horizontal Illuminance (lux)	Manufacturer C	D	E	F	G	H
300	0.12	0.13	0.12	0.15	0.13	0.15
325	0.13	0.14	0.13	0.16	0.14	0.17
350	0.14	0.15	0.14	0.18	0.15	0.18
375	0.15	0.16	0.15	0.19	0.16	0.19
400	0.16	0.17	0.16	0.20	0.17	0.20
425	0.17	0.17	0.17	0.21	0.17	0.21
450	0.17	0.18	0.18	0.22	0.18	0.22
475	0.18	0.19	0.19	0.22	0.19	0.23
500	0.19	0.20	0.20	0.23	0.20	0.23





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Summary

- Bottom lines for health impacts from light
  - Must consider all physical attributes - amount, duration, timing and spectrum; not just spectrum
  - Get the metrics and units right!
    - CCT is useless and often misleading for characterizing the light stimulus
    - Photopic illuminance has very limited utility for characterizing how light stimulates the retina
  - When assessing risk, must consider the "use cases"

Thank you.

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