Health Effects of Solid State Lighting:

Glare

Photobiological Safety

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Online – November 21, 2024

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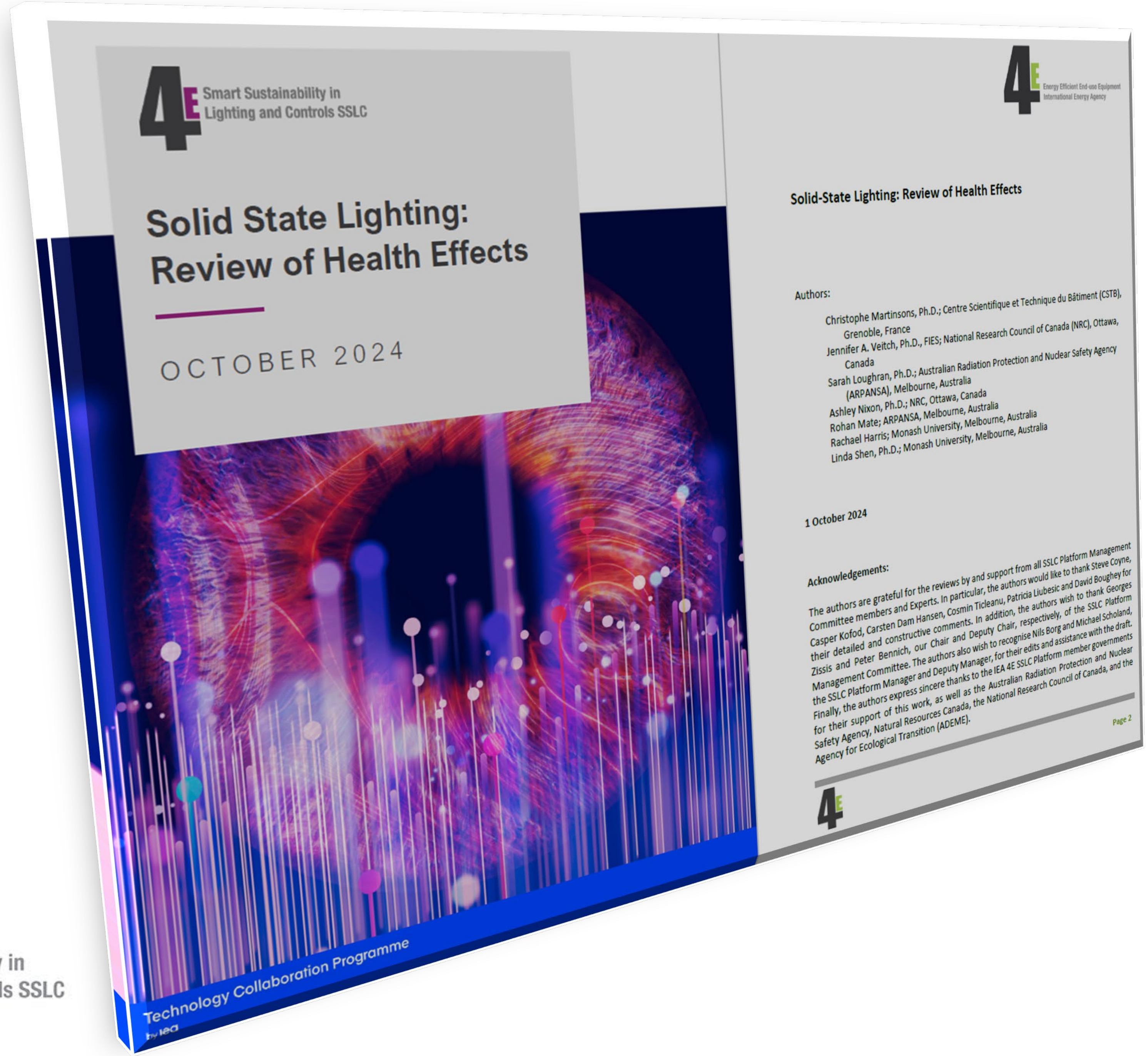

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Solid State Lighting: Review of Health Effects

OCTOBER 2024

Technology Collaboration Programme by iea

Energy Efficient End-use Equipment International Energy Agency

Solid-State Lighting: Review of Health Effects

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1 October 2024

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Why review the health effects of Solid-State Lighting (SSL)… again?

- Many users still complain…
- Individual exposure to LEDs has globally increased
- Advances in physiology and medicine: new research results have improved our understanding of the effects of light
- Inclusiveness: lighting should be adapted to everyone!
- The existence of sensitive people should be recognized
- Sensitive populations and their specific needs should be identified

Identify the features of LED lamps and luminaires that can be improved to achieve better outcomes in terms of health and well-being

Objectives of this review

- To provide guidance to the lighting industry
  - Reducing negative health effects goes along with improving lighting quality and individual well-being and customer satisfaction
- To improve public health and the awareness of the public
  - Protect sensitive people against adverse effects of light
  - Inform of needs to proper exposure to light - and to darkness - in everyday life
- To improve lighting regulations, standards, procurement specifications
- To identify areas where more research is needed

Scope

- Focus on general lighting products:

  Lamps and luminaires for general interior lighting, street and road lighting

- Out of scope: automotive lighting, light sources that are not lighting products (toys, displays, etc.)

An international collaboration, on behalf of several governments

- Work initiated by the IEA Technology Collaboration Program 4E (energy-efficient end-use equipment), Solid-State Lighting Annex, now SSLC platform
- Update of a first report published in 2014 by the IEA 4E SSL Annex
- Collaboration between three research teams from public institutes in Australia (ARPANSA), Canada (NRC Canada) and France (CSTB) between 2019 and 2024.
- Funding provided by AU, CA and FR governments, and from the SSL Annex

Method

- This work is based on the analysis of:

  - Reviews published during the last decade
  - Published research papers (literature search 2015-2024) when there were no reviews
  - Standards, guidelines, collective appraisal reports, technical reports

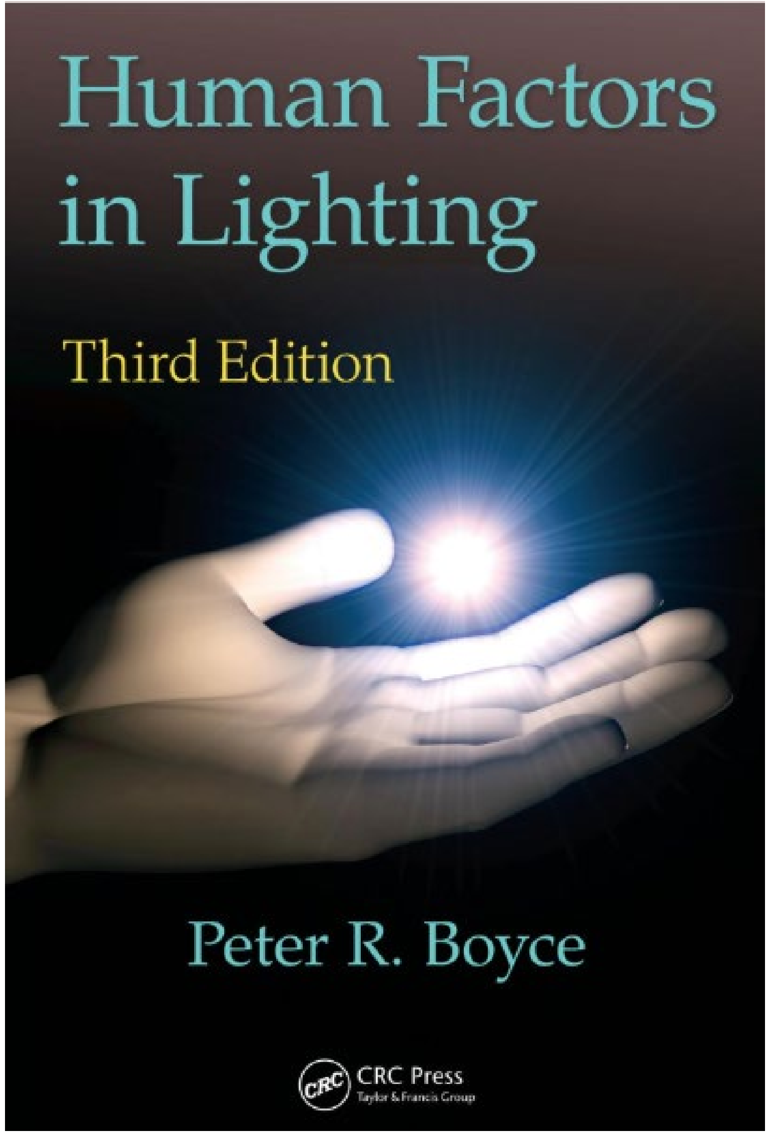
I. Glare

Glare

- The fastest adverse effect to be experienced with lighting
- Physiological phenomenon --- “not in your head”
- The #1 complaint about lighting, very commonly expressed by users
- Glare immediately decreases visual performance, and increases the risk of accidents and falls
- Glare has health consequences after prolonged exposure
- There are very sensitive populations

Different forms of glare

Boyce, Peter R. *Human Factors in Lighting, Third Edition*. CRC Press, 2014.



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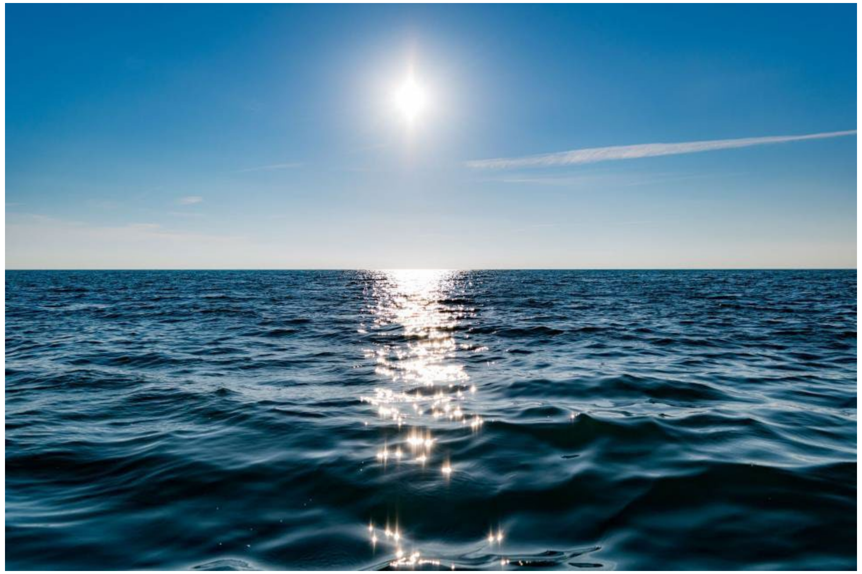
Saturation glare

Too much light, levels exceeding the upper limit for vision

The entire visual field is saturated, sensation of pain

Levels hazardous to the eye (cornea and retina) --- photobiological safety



Adaptation glare

- Transient phenomenon (rapid increase of light level)
- Vision generally takes a few seconds to adapt

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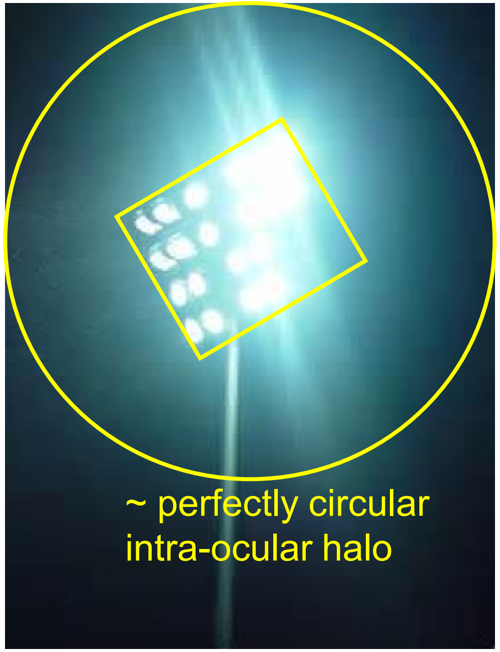
Disability Glare

Halo around bright lights on dark background is caused by light diffusion in the eye

- Reduce the visibility of dimmer objects
- Strong influence of age (included in indices TI and GR)
- Mostly experienced at night
- **Can be experienced with or without discomfort**
- No research papers investigating disability glare from LEDs vs older technologies (anecdotal reports show no difference)

Disability glare (veiling halo around bright sources)



Young subject

Older subject

The halo is created inside the eye (intra-ocular)

Discomfort glare (luminance contrast)

- Very common with indoor lighting, but still difficult to assess
- One of the top-rated factor of indoor environmental quality (IEQ)
- Large body of research work since a more than a century
- New concerns with LEDs and SSL in general

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Discomfort glare

- High luminance contrast (cd/m²)
- Not necessarily high illuminance (lux) at the eye
- Difficulty for the visual system to maintain a high dynamic range in the field of vision for a « long » time
- Consequence of this difficulty: discomfort, annoyance, stress, aversion response
- However, visual performance can be maintained (no halo is visible around light source)… with efforts (and with consequences)

The term « discomfort glare » is somewhat misleading, suggesting a psychological phenomenon ('it's all in your head'). The term « contrast glare » would be more adapted. Discomfort is a subjective consequence of glare ('discomfort FROM glare'). Discomfort is a subjective outcome that can be assessed by psychological methods.

Discomfort glare

Discomfort is traditionally assessed using psychophysics: individual judgements based on controlled stimuli, psychometric scales. Protocols not always free of bias.

Discomfort glare is physiological, it is a consequence of an increased difficulty of the visual system to work in a highly contrasted environment, reflected by a higher activity of the visual cortex

New methods have emerged to monitor physiological and behavioral response to glare, including eye-tracking, EEG, fMRI, brain oximetry

Hamedani, Z., E. Solgi, T. Hine, H. Skates, G. Isoardi, and R. Fernando. "Lighting for Work: A Study of the Relationships among Discomfort Glare, Physiological Responses and Visual Performance." *Building and Environment* 167 (2020)

Lee, H.-S., J.-Y. Kim, M. Subramaniyam, S. Park, and S.-N. Min. "Evaluation of Quantitative Glare Technique Based on the Analysis of Bio-Signals." *Ergonomics* 60, no. 10 (2017)

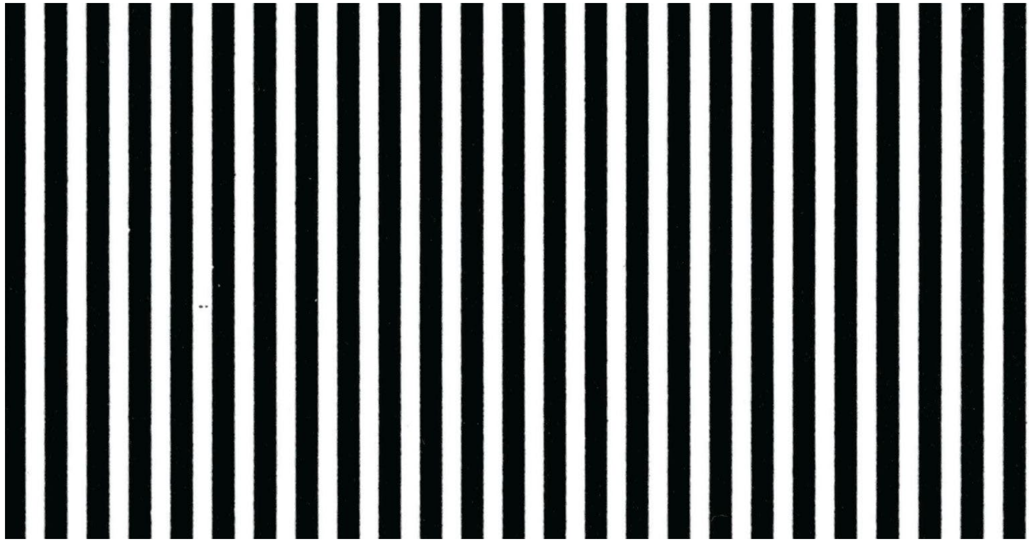
Iodice, Matthieu. "Méthodes de caractérisation psychophysique et physiologique de l'éblouissement d'inconfort en éclairage artificiel intérieur. Étude de l'influence du contenu spectral des sources lumineuses." PhD. Thesis, ENTPE et Université de Lyon, 2020.

What was learned from physiological responses?

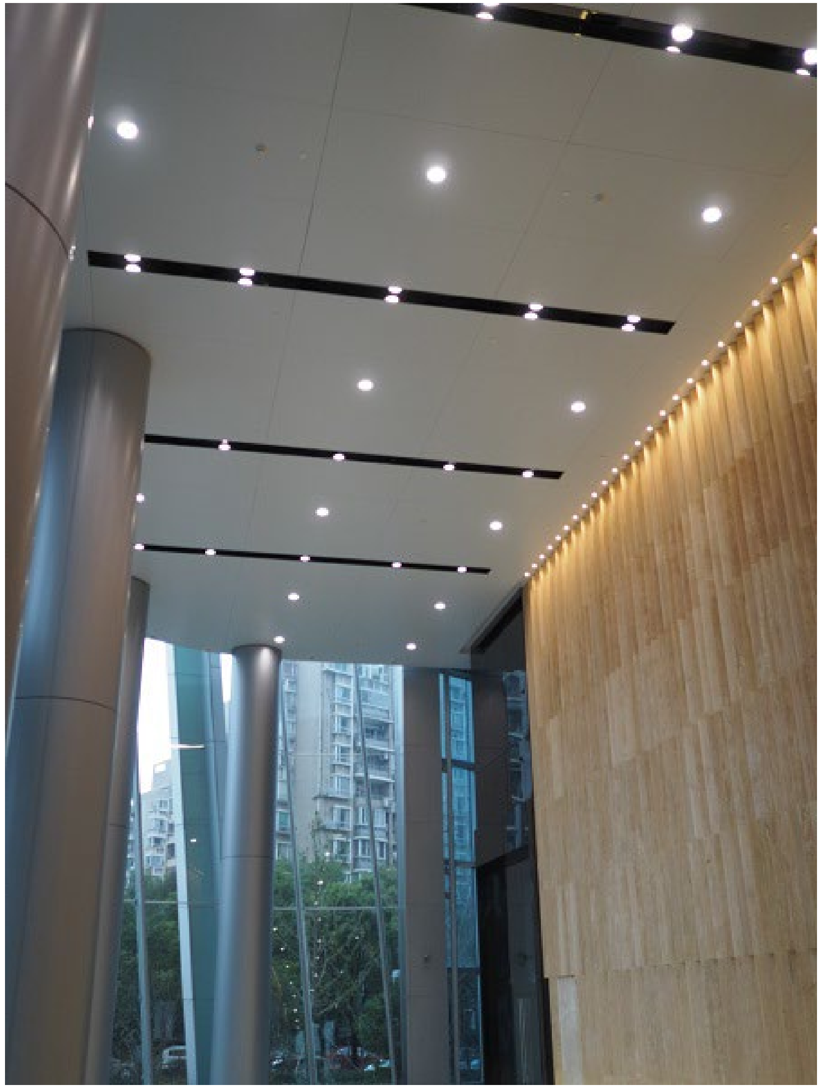
- They have provided direct proofs that reading performance is decreased under a glaring source
- Glare influences many ocular parameters : saccade speed and amplitude, fixation time, blink rate, pupil size, pupillary unrest index. These are not consciously perceived.
- Promising approach to study glare but more research is need to identify the most significant parameters (task dependent)

Discomfort from glare: neural correlates

- There is a link between visual discomfort and increased blood flow in the brain (hemodynamic response)
- **Periodic patterns** in the field of view (critical spatial frequencies) create visual discomfort (related to the effect of non-uniformity)



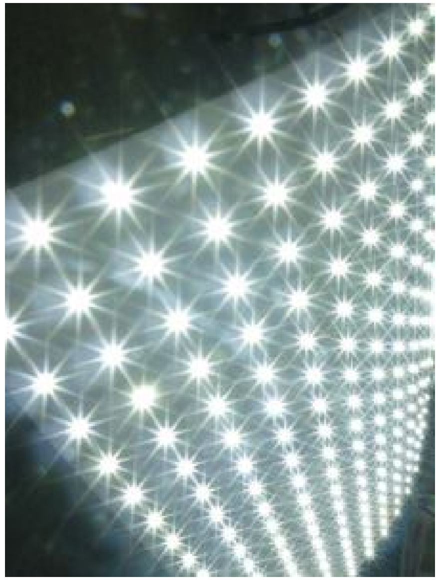
Wilkins, Aj. “A Physiological Basis for Visual Discomfort: Application in Lighting Design.” *Lighting Research & Technology* 48, no. 1 (2016).



Non-uniformity of luminance

Luminance non-uniformity (LED arrays) increases discomfort

- Well-understood phenomena in indoor lighting (modified UGR index)
- Many SSL streetlights are non-uniform, but no study investigated outdoor luminaires seen at close range.



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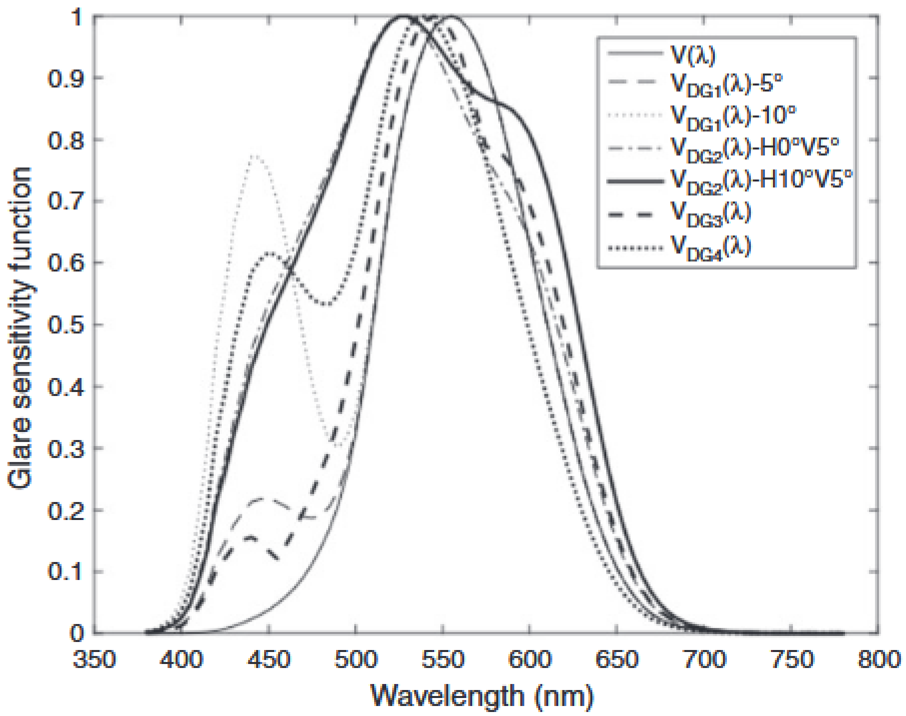
Influence of spectrum / color on discomfort glare

- Research have consistently showed that cold-white LEDs are more glary than warm-white LEDs, all things being equal
- Several models of spectral sensitivity to discomfort glare were published
  - Varies between peripheral and central vision
  - Role of short-wavelength cones
- No agreement (yet) on the spectral sensitivity curve



Yang, Y, Ronnier M Luo, and WJ Huang. "Assessing Glare, Part 3: Glare Sources Having Different Colours." *Lighting Research & Technology* 50, no. 4 (2018)

Bullough, J.D. « Spectral Sensitivity for Extrafoveal Discomfort Glare ». *Journal of Modern Optics* 56, n° 13 (2009)

$$V_{DG1}(\lambda) = V_{10}(\lambda) + kS(\lambda)$$

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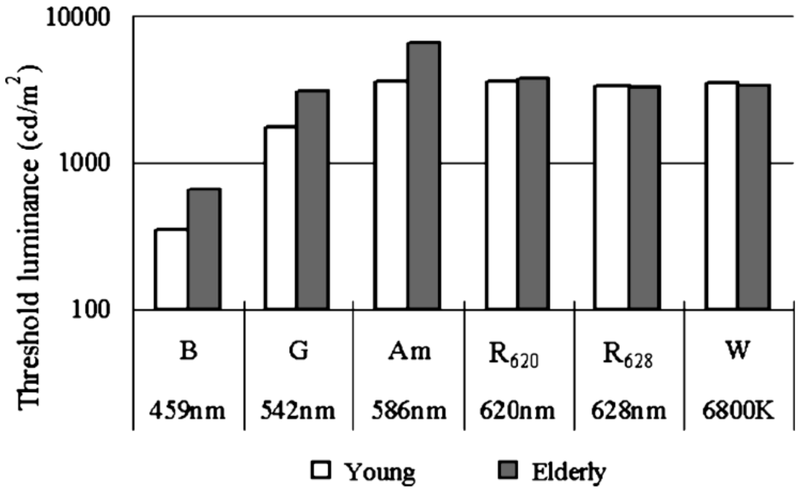
Effects of age on glare

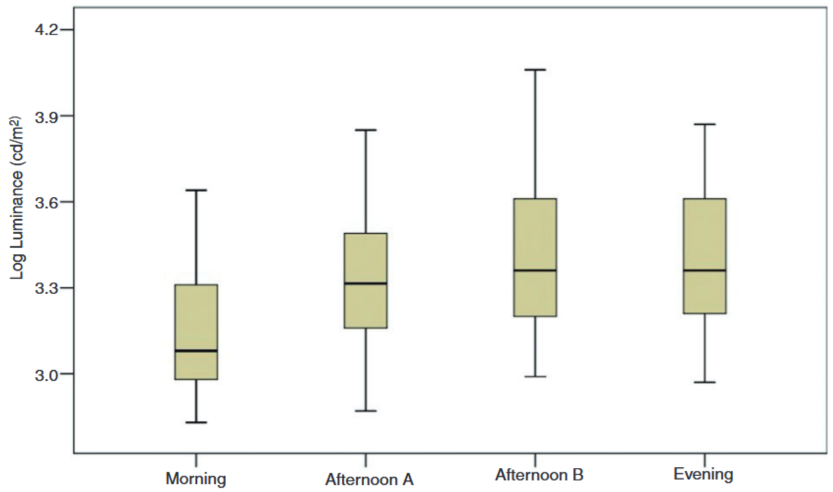
- Children and young adults experience more discomfort from glare, and they experience it faster than older adults
- One study showed that after a prolonged exposure to discomfort glare, the visual performance of subjects over 50 decreased in low light conditions: delayed effects of long exposure to a glare source



Kimura-Minoda, T., and M. Ayama. "Evaluation of Glare from Color LEDs for Young and Elderly." *Journal of Light and Visual Environment* 36, no. 2 (2012)

Circadian aspects of discomfort glare

- Limited number of studies
- Discomfort from glare increases during the day (greater sensitivity in the morning)
- Discomfort from glare is influenced by the chronotype
  - People with early chronotypes are not as sensitive to glare
- Mechanism is not known, current investigations on the role of ipRGCs



Kent, MG, S Altomonte, PR Tregenza, and R Wilson. “Discomfort Glare and Time of Day.” *Lighting Research & Technology* 47, no. 6 (2015)

Health effects of glare

- Glare triggers and aggravates headaches in people suffering from migraines
  - Influence of the spectrum (green light is the least active) (Martin, 2021)
- Photophobia (fear of light) is an extreme form of discomfort from glare experienced by the most sensitive people
  - Albilali et al “Photophobia: When Light Hurts, a Review.” Current Neurology and Neuroscience Reports 18, no. 9 (2018)
  - Possible non-visual pathways through the trigeminal nerve (Matynia, 2015), Possible action of light on pain-processing mechanisms (Martenson, 2016)
- Prolonged exposure to glare contributes to asthenopic syndromes (eye fatigue, eyestrain) & muscular pains
- Safety issues: accidents, falls, occupational hazards

Albilali, Abdul, and Esma Dilli. “Photophobia: When Light Hurts, a Review.” *Current Neurology and Neuroscience Reports* 18, no. 9 (2018)

Indoor lighting metrics for discomfort glare

- UGR and UGR small source

  CIE 117 (1995)

- UGR Tables for indoor lighting

  CIE 190 (1190)

- UGR non-uniform sources

  CIE 232:2019 Discomfort Caused by Glare from Luminaires with a Non-Uniform Source Luminance

Glare models used in street/road lighting

- CGM (1976) et CBE (1979) → Adrian's model (1991)
- Other models: Vos (2003), Bullough (2008), Lin (2015)

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SAGE journals

Article

Assessment of pedestrian discomfort glare from urban LED lighting

C Villa, PhD, R Bremond, PhD, and E Saint-Jacques, MSc

Discomfort Glare from Several Sources: A Formula for Outdoor Lighting

Joffrey Girard, Céline Villa & Roland Brémond

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Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

ISBN 978-3-902842-92-3
DOI: 10.25039/TR.243.2021

TECHNICAL REPORT

Discomfort Glare in Road Lighting and Vehicle Lighting

CIE 243:2021 reprint 2023

UDC: 628.931, 628.987, 612.84

Descriptor: Electrical lighting design, Evaluation of lighting installations, Vision

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Outdoor lighting metrics

- GR Index (CIE 112:1994) assesses **disability glare** caused by stadium luminaires (does not reflect discomfort). Requirement of the NF EN 12193 standard
- TI index: **disability glare** of vehicle drivers by road lighting (does not reflect discomfort). Requirement of the NF EN 13201-2 standard
- The UGR, UGRsmall and UGRnon-uniform indices are not validated outdoors
- The effect of non-uniformity of luminaires seen at close range at night by pedestrians has not been sufficiently studied
- The effects of multiple sources in the field of view are currently being investigated

Main conclusions on glare

Glare

#1 source of complaints

Alters vision (during and after exposure)

Triggers headaches, responsible for eyestrain (during and after long exposure)

Importance of product optical design (size, luminance, and its non-uniformity)

Influence of spectral distribution

Neural mechanisms were studied but are still not fully understood, influence of age

Recommendations

- Favor large area uniform SSL luminaires in indoor lighting when the exposure time is long (schools, offices, etc.)
- Non-uniform luminaires for indoor applications should be assessed using the proper correction of the UGR
- The optical design of SSL products should be improved: hide the LEDs from direct view, use diffusers
- If not possible, provide guidance to the lighting designers, installers, and users : use of a shading device, do not direct towards the eye, etc.

Sensitive people & highly exposed people

Glare

Migraineurs, people adverse to strong lights
Children and young adults
Links with high sensitivity to temporal light modulation

Night workers (intrinsic sensitivity might be higher)

Drivers and pedestrians at night
Workers using strong lights: lighting professionals, athletes, artist in stadiums and on stage, etc.

Recommendations for sensitive people

Migraineurs, people adverse to strong lights, children

- Avoid direct viewing of high-luminance SSL sources
- Reduce source luminance and luminance contrasts in the visual field
- Avoid periodic patterns
- Use cold-white light with care, only if necessary

Older adults

- Avoid long exposure to glare (possible delayed effects on vision)

People working at night are more exposed and more sensitive

- Without daylight in the visual field, luminance contrasts are increased
- Increased discomfort with circadian phase misalignment

Knowledge gaps and research priorities with glare

Effect of non-uniformity (LED arrays) at close range in outdoor lighting

Combined effect of multiple glare sources in outdoor lighting

Missing agreement on the spectral sensitivity

Role of each photoreceptor type, including ipRCGs

Influence of the circadian clock

Neural mechanisms leading to visual discomfort and light aversion

Influence of age: studies with children are needed

Dose-effect relation between glare and headaches, glare and eyestrain

Difficult to carry out « provocation » studies with sensitive people for ethical reasons

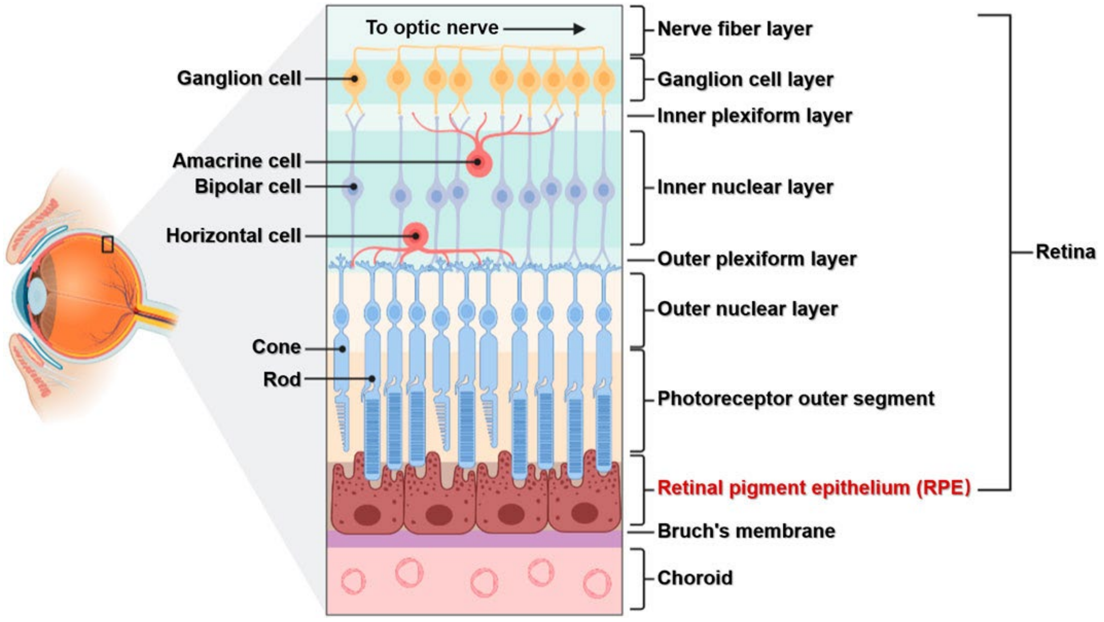
II. Photobiological safety

Photobiological safety refers to acute effects of optical radiation on the eye and the skin

- UV, VIS and IR radiations induce thermal and photochemical effects on the skin and on the eye
  - Unless with certain rare conditions (e.g. lupus), visible light from LEDs is harmless for the skin
- UV and IR may cause injuries to the cornea, iris and lens (e.g. cataract, photokeratitis).
  - Unlike discharge lamps, including fluorescent lamps, and halogen lamps, most SSL products emit no IR and no UV
- **Retinal hazards**
  - visible light, near infrared, UV between 300 – 380 nm for sensitive people

The retina

- Cones
  - concentrated in the fovea
  - detailed vision at high luminance and colour detection
- Rods
  - dominate in the periphery
  - image detection at low luminance
- Intrinsically photoreceptive retinal ganglion cells (ipRGCs)
  - located throughout the retina
  - detect irradiance



Yang, S., Zhou, J., & Li, D. (2021). Functions and diseases of the retinal pigment epithelium. *Frontiers in Pharmacology, 12, 727870.* https://doi.org/10.3389/fphar.2021.727870.

Retinal hazards

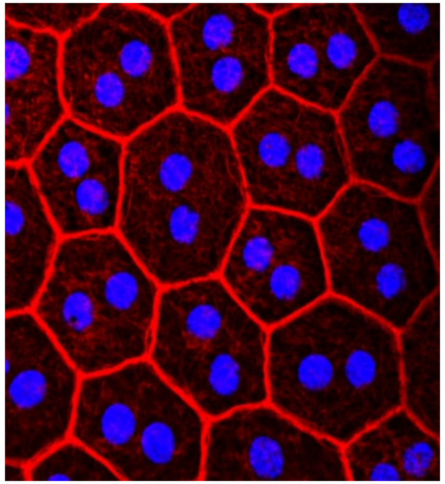
- Retinal thermal hazard
  - Wide range 380 nm to 1 400 nm
  - Never demonstrated with LEDs used in lighting systems
- Retinal photochemical hazard type I:
  - Chronic exposure to bright light (associated with high intensity saturation glare, death of photoreceptors) ~flat spectral sensitivity
- Retinal photochemical hazard type II: the “blue light hazard” (BLH)
  - Photochemical reactions are triggered by short wavelength photons (blue, violet, UV) in the cells of the retinal pigmented epithelium (RPE). Peak at 430 - 440 nm
  - Cell death mainly in the RPE, extending to photoreceptors
- Glare may or may NOT happen with the blue light hazard
  - Glare is not necessarily the first signal of a photobiological hazard
  - Visual stimulus is greatly reduced in the blue-violet spectral range
  - Blue light alone does not produce a strong aversion response

A case report of an eye injury caused by exposure to a 5W white LED torch light.

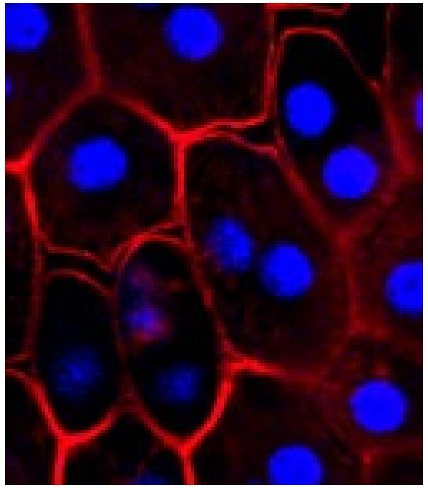
"For our patient, OCT findings of outer retina disruption were particularly similar to those presented in patients with solar maculopathy, welding arc maculopathy, or maculopathy associated with viewing of a plasma flash produced by a femtosecond laser"

Zhang, Li, Chun-Yan Lei, Zhi-Cheng Zhang, Jin-Yue Gu, and Mei-Xia Zhang. "Accidental Macular Injury from Short-Term Exposure to a Handheld High-Intensity LED Light." *Heliyon* 9, no. 8 (2023)

RPE of rat retina



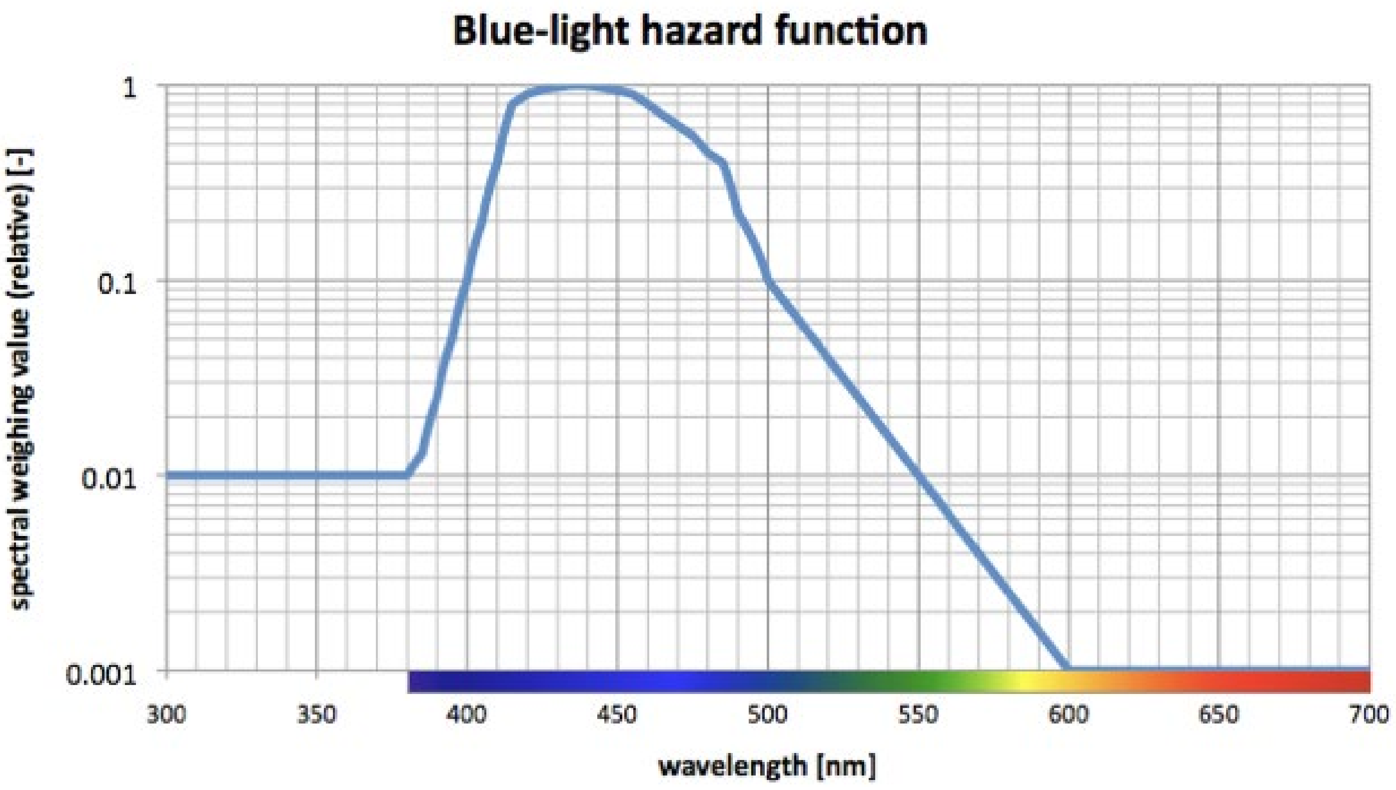
non illuminated



After 6h exposure

Jaadane, I et al. "Effects of White Light-Emitting Diode (LED) Exposure on Retinal Pigment Epithelium *in Vivo*." *Journal of Cellular and Molecular Medicine* 21, no. 12 (2017)

The B(λ) function



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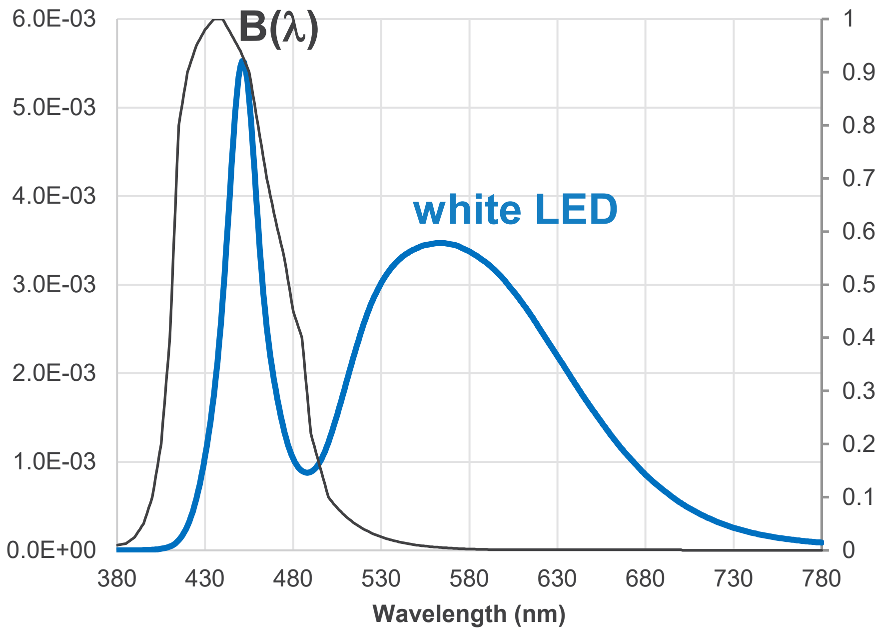
How “bad” is the blue peak?

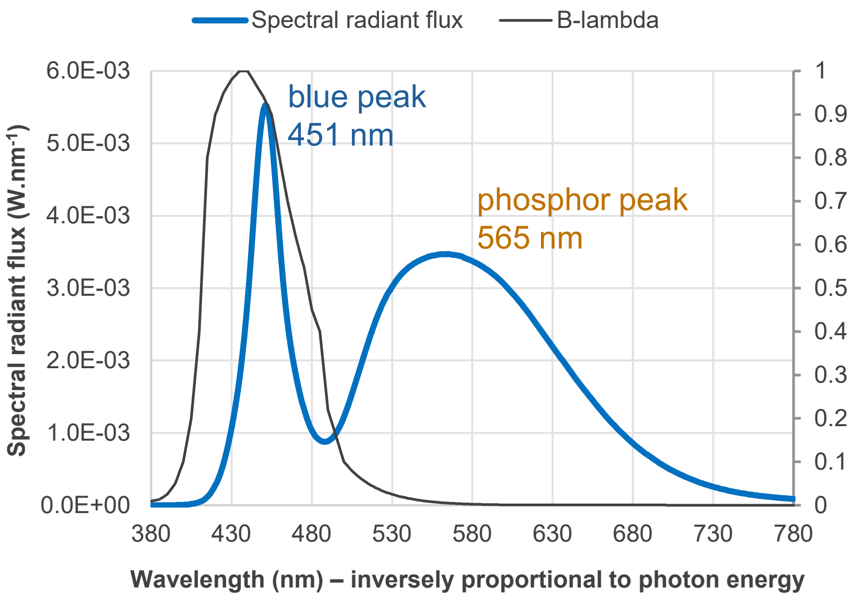


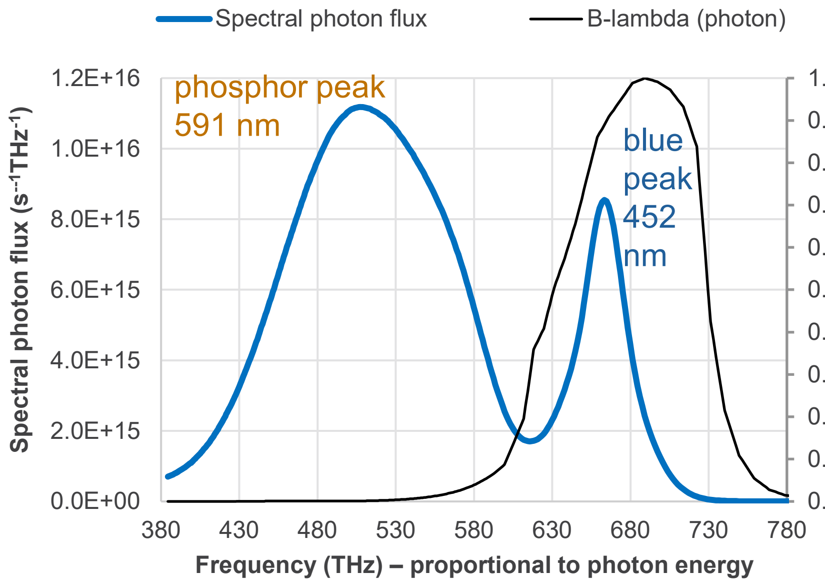
Beware of this type of interpretation!

Reconsidering the spectral distribution of light: Do people perceive watts or photons?

Lighting Research & Technology 2024 (open access)

C Martinsons[a], F Behar-Cohen[b,c,d], T Bergen[e], P Blattner[f], M Herf[g], C Gronfier[h], K Houser[i], S Jost[j], M Nilsson Tengelin[k], G Obein[l], L Schlangen[m], L Simonot[n], M Spitschan[o,p], A Torriglia[b] and J Zeitzer[q]





Same LED; two different representations of the same spectral distribution

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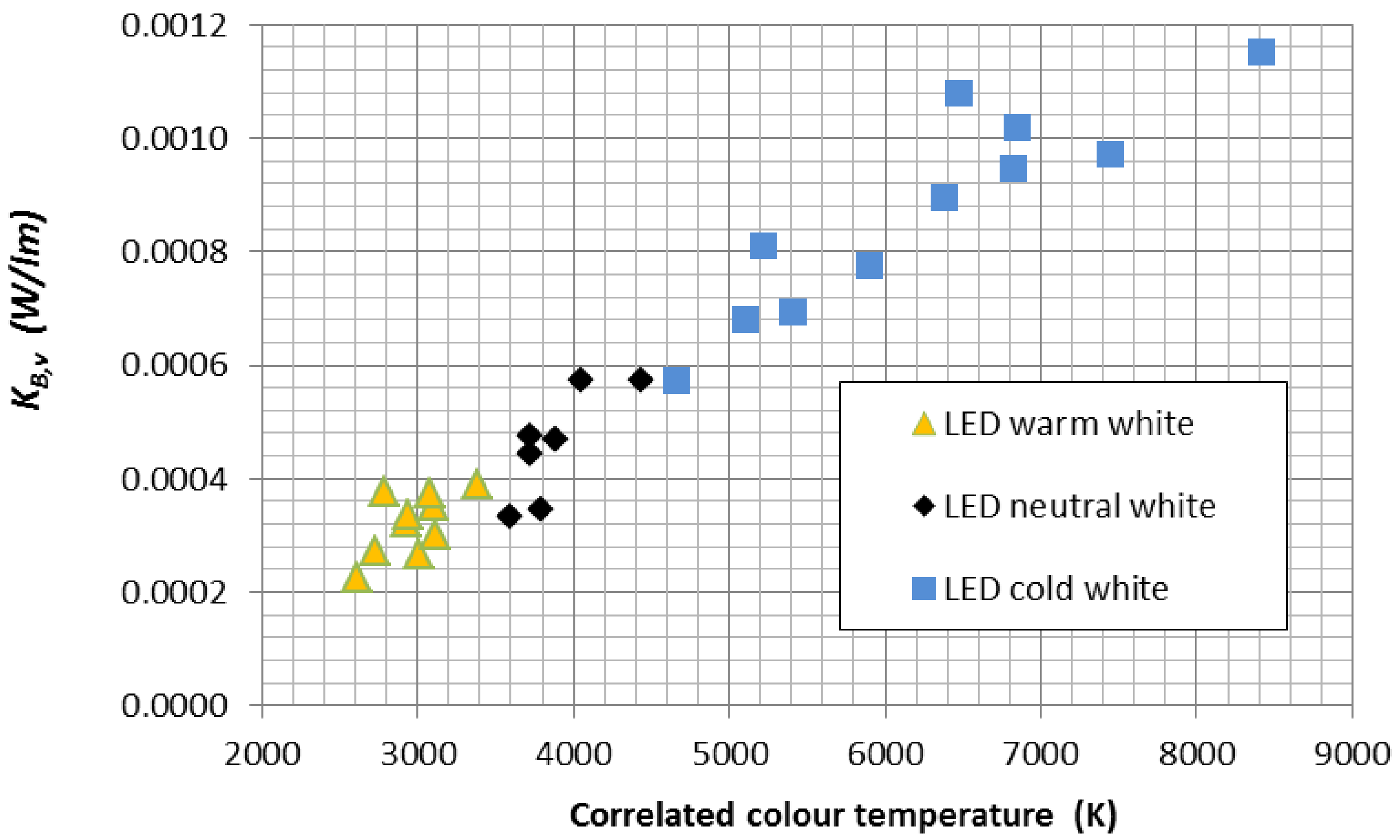
Blue light hazard efficacy of luminous radiation



CIE TN 002:2014

blue light hazard efficacy of luminous radiation (of a source)
$K_{B,v}$
quotient of the blue light hazard weighted radiant flux[1], Φ_B, to the luminous flux, Φ_v,

$$K_{B,v} = \frac{\Phi_B}{\Phi_v} = \frac{\int \Phi_{e,\lambda}(\lambda) \cdot B(\lambda) \cdot d\lambda}{K_m \cdot \int \Phi_{e,\lambda}(\lambda) \cdot V(\lambda) \cdot d\lambda}$$

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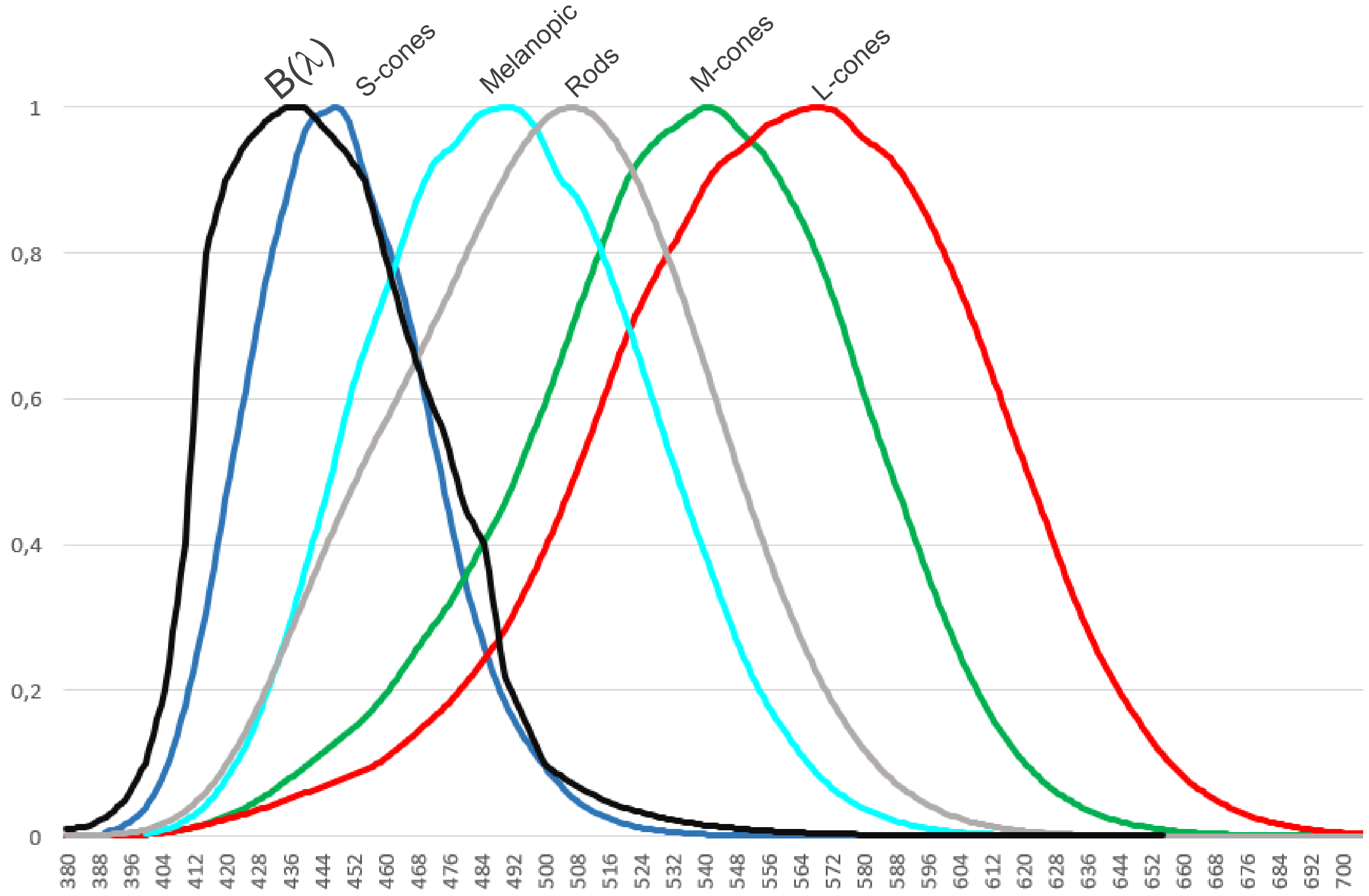
B(λ)
S-cones
Melanopic
Rods
M-cones
L-cones
1
0,8
0,6
0,4
0,2
0
380
388
396
404
412
420
428
436
444
452
460
468
476
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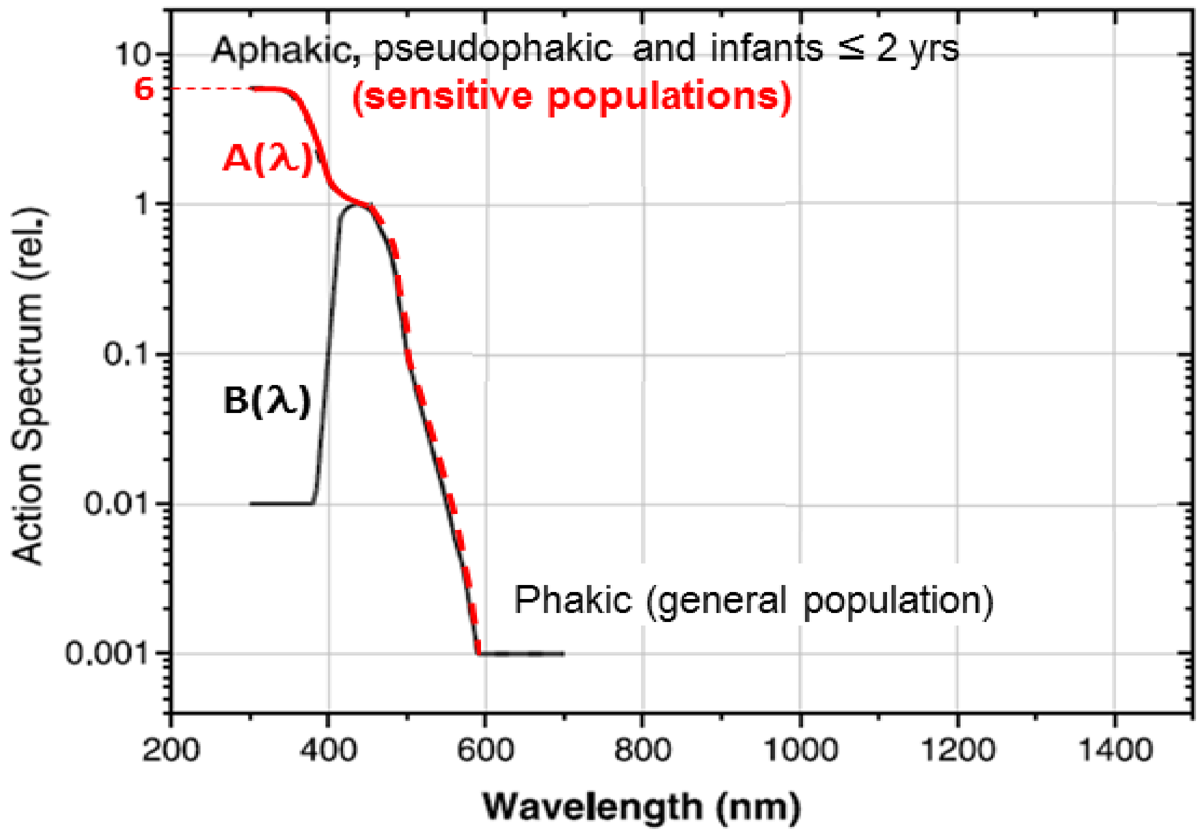
700

People with greater transparency of the eye
The A(λ) function



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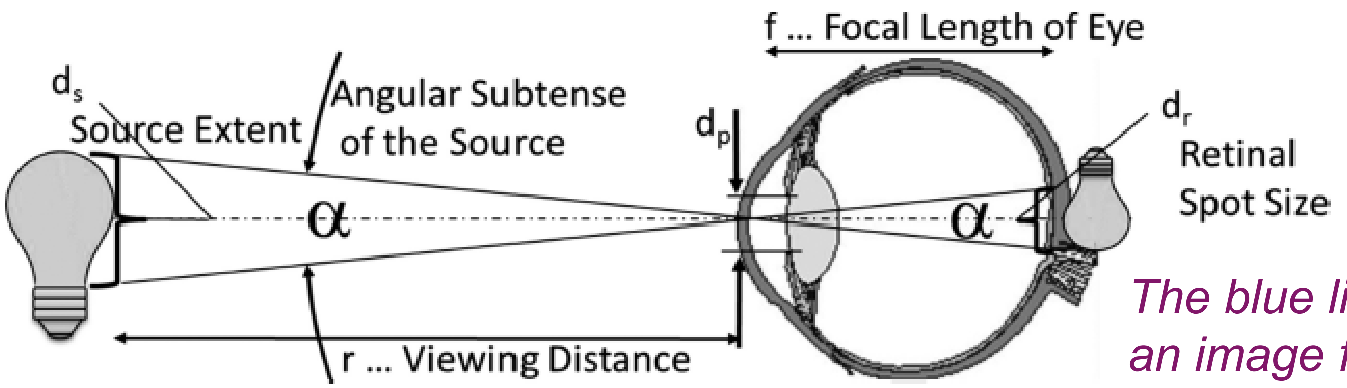
Normative limits for the BLH



The blue light hazard is an image forming effect

Current ICNIRP limits

Damage threshold on the retina: 20-30 J/cm² (retinal irradiance dose at 440 nm), reported by Ham et al. 1976, 1979

Limit value on the retina: 2.2 J/cm² (safety factor of 10)

Using a model of an adult eye, this limit was transposed into a source emission limit (B(λ)-weighted radiance dose) of 10^6 J/m²/sr.

ICNIRP. "ICNIRP Guidelines on Limits of Exposure to Incoherent Visible and Infrared Radiation." *Health Physics* 105, no. 1 (2013)

The blue light hazard was detected below the current exposure dose

- The detection of retinal damage has greatly improved over the last decade
- Studies on rats and living macaques showed retinal damage with exposures below the current limit set by the ICNIRP

Zhang, Jie, Ranjani Sabarinathan, Tracy Bubel, Wuao Jia, David R. Williams, and Jennifer J. Hunter. “Spectral Dependence of Light Exposure on Retinal Pigment Epithelium Disruption in Living Primate Retina.” *Investigative Ophthalmology & Visual Science* 65, no. 2 (2024)

Jaadane, I., G. Villalpando Rodriguez, P. Boulenguez, S. Carré, I. Dassieni, C. Lebon, S. Chahory, F. Behar-Cohen, C. Martinsons, and A. Torriglia. “Retinal Phototoxicity and the Evaluation of the Blue Light Hazard of a New Solid-State Lighting Technology.” Scientific Reports 10, no. 1 (2020)

Jaadane, Imene, Gloria Elisa Villalpando Rodriguez, Pierre Boulenguez, Sabine Chahory, Samuel Carré, Michèle Savoldelli, Laurent Jonet, Francine Behar-Cohen, Christophe Martinsons, and Alicia Torriglia. “Effects of White Light-Emitting Diode (LED) Exposure on Retinal Pigment Epithelium in Vivo.” Journal of Cellular and Molecular Medicine 21, no. 12 (2017)

Hunter, Jennifer J., Jessica I. W. Morgan, William H. Merigan, David H. Sliney, Janet R. Sparrow, and David R. Williams. “The Susceptibility of the Retina to Photochemical Damage from Visible Light.” Progress in Retinal and Eye Research 31, no. 1 (2012)

The retina of children is more exposed

- The child's eye is more « open » and transmits more light
  - "ICNIRP adult": pupil diameter = 3 mm, focal length = 17 mm — $3^2/17 = 0.53$ relative aperture
  - Newborn child : pupil diameter = 4.7 mm, focal length = 15.7 mm — $4{,}7^2/15.7 = 1{,}41$ relative aperture
  - The crystalline lens is more transparent
  - UV filtering by crystalline lens stabilizes at around 10 years old
  - Eye growth slows down after the age of 13

- With a similar illuminance at the eye, retinal exposure can be up to 3 times higher for children than for adults

- The aversion response is not fully developed in children, and it can be by-passed on purpose

Point, S. "Blue Light Hazard: Are Exposure Limit Values Protective Enough for Newborn Infants?" *Radioprotection* 53, no. 3 (2018)

The retina is more sensitive at night

- Studies on diurnal animals revealed circadian variations of retinal functions
- Retinal phototoxicity increases at night, when the retina is supposed to rest and clean itself (phagocytosis)

Verra, Daniela M., Benjamin S. Sajdak, Dana K. Merriman, and David Hicks. “Diurnal Rodents as Pertinent Animal Models of Human Retinal Physiology and Pathology.” *Progress in Retinal and Eye Research* 74 (2020)

Protective effect of longer wavelengths

- Positive results with « photobiomodulation », a technique using red and near-infrared (NIR) light to heal damaged tissues
- Positive effects on the retina: accelerated healing through increased phagocytosis and mitochondrial activity of RPE cells
- Promising medical applications
- In general lighting, not enough results to demonstrate that enriching the spectrum with red and NIR light could attenuate the blue light hazard

Albarracin et al. “Photobiomodulation Protects the Retina from Light-Induced Photoreceptor Degeneration.” Investigative Ophthalmology & Visual Science 52, no. 6 (2011)

Del Olmo-Aguado et al.“Red Light of the Visual Spectrum Attenuates Cell Death in Culture and Retinal Ganglion Cell Death in Situ.” Acta Ophthalmologica 94, no. 6 (2016)

Fuma et al. “Photobiomodulation with 670 nm Light Increased Phagocytosis in Human Retinal Pigment Epithelial Cells.” Molecular Vision 21 (2015)

The IEC 62471 / CIE S009 standard (photobiological safety of lamps): hazard classification for adults without eye pathology

Measure blue light radiance of source at 200 mm within specified field of view angle → Compute exposure time needed to reach the ICNIRP emission limit value (10^6 J/m²/sr) → Risk Group

Exposure time to reach the exposure limit	Risk Groups
$t \geq 10\ 000$ s	Risk Group RG 0: no risk
$100 \text{ s} \leq t < 10\ 000$ s	Risk Group RG 1: low risk
$0.25 \text{ s} \leq t < 100$ s	Risk Group RG 2: moderate risk
$t < 0.25$ s	Risk Group RG 3: high risk

Published product emission data

- **SSL products sold in the last 5 years for domestic and office lighting are comparable with halogen and fluorescent lamps in terms of blue light radiance : RG0 (no risk), RG1 (low risk)**
- UV, blue and cold white LEDs used without diffusing optics may harm the retina after exposures as short as 15 s. **Most are RG2.**
- No data on the blue light radiance of high-power professional LED luminaires (stadium, architectural, industrial, and road lighting)

Bullough, John D., Andrew Bierman, and Mark S. Rea. “Evaluating the Blue-Light Hazard from Solid State Lighting.” International Journal of Occupational Safety and Ergonomics 25, no. 2 (2019)

Dain, S.J. “The Blue Light Dose from White Light Emitting Diodes (LEDs) and Other White Light Sources.” Ophthalmic and Physiological Optics 40, no. 5 (2020)

Heßling, M., P.S. Kölbl, P. Singh, S. Deuchler, D. Sinning, F.H.J. Koch, and C. Lingenfelder. “Hazards posed by LEDs?: A comparative study.” Ophthalmologe 116, no. 7 (2019)

James, Robert H., Robert J. Landry, Bennett N. Walker, and Ilko K. Ilev. “Evaluation of the Potential Optical Radiation Hazards with Led Lamps Intended for Home Use.” Health Physics 112, no. 1 (2017)

Leccese, F., V. Vandelanotte, G. Salvadori, and M. Rocca. “Blue Light Hazard and Risk Group Classification of 8 W LED Tubes, Replacing Fluorescent Tubes, through Optical Radiation Measurements.” Sustainability 7, no. 10 (2015).

O’Hagan, J B, M Khazova, and L L A Price. “Low-Energy Light Bulbs, Computers, Tablets and the Blue Light Hazard.” Eye 30, no. 2 (2016)

Salsi, S., and A. Barlier-Salsi. “Exposition aux dispositifs d’éclairage scénique : risque pour la santé des professionnels du spectacle vivant ou enregistré.” Radioprotection 48, no. 3 (2013)

The sky, the sun, and LEDs

High illuminance
Low luminance → Blue sky

Low illuminance
High luminance → White LED (6500 K) at 0.5 m

Source	Illuminance at cornea (lx)	Source luminance ($cd \cdot m^{-2}$)	Effective luminance ($cd \cdot m^{-2}$)	Blue-light hazard weighted radiance, L_b ($W \cdot m^{-2} sr^{-1}$)	Permissible exposure time per Standard No. CIE S 009 [44]
Blue sky	10,000	4000	4000	6.2	Indefinite (44 h)*
Fluorescent lamp (T8 RE, 4100 K) at 0.5 m	750	10,000	10,000	5.6	Indefinite (50 h)*
White LED (3000 K) at 0.5 m	98	1.7×10^7	1.0×10^6	388	43 min*
White LED (4000 K) at 0.5 m	98	1.7×10^7	1.0×10^6	510	33 min*
White LED (6500 K) at 0.5 m	98	1.7×10^7	1.0×10^6	858	20 min*
Incandescent lamp filament at 0.5 m	240	1.2×10^7	2.5×10^6	858	20 min*
Royal blue LED 500 mW at 0.5 m	29	5.1×10^6	1.7×10^5	2620	6.4 min*
Royal blue LED 3 W at 0.5 m	99	2.8×10^6	1.0×10^6	15,000	1.1 min
Blue LED light box at 0.5 m	600	9000	9000	60	Indefinite (4.6 h)*
Sun	100,000	1.6×10^9	1.6×10^9	1.2×10^6	~1 s

Bullough, John D., Andrew Bierman, and Mark S. Rea. "Evaluating the Blue-Light Hazard from Solid State Lighting." *International Journal of Occupational Safety and Ergonomics* 25, no. 2 (2019).

Main conclusions on the photobiological safety

Photobiological Safety

The blue light hazard remains a concern

Consistent detection of retinal damage by blue light below the current exposure limit

Retinal phototoxicity increases at night

Children are not sufficiently protected by current standards and regulations

Protective effects of red/NIR light on the retina were found

Sensitive people & highly exposed people

Photobiological Safety

Children
People with retinal diseases
People wearing lens implants
Night workers

Workers using strong lights: lighting professionals, athletes, artist in stadiums and on stage, etc.

Recommendations

- Update the blue light hazard exposure limit
- Update photobiological safety standards by considering sensitive people, including children
- Do not apply more permissive standards before these updates
- Strengthen photobiological safety requirements for people exposed at night and people with reduced aversion response to bright light

Knowledge gaps, research priorities

- Emission data of high-power professional LED luminaires
- Emission data of UV phosphor-converted white LEDs
- Effects of simultaneous exposure to blue and red/NIR light on the retina (short + long wavelengths). Benefits of “spectrum enrichment” in preventing retinal damage
- Influence of age and age-related retinal pathologies on the retinal sensitivity to short wavelength light

Policy recommendations for glare and PBS

- Manufacturers: Target product design to minimize the possibility of glare and retinal hazard
- Standardization bodies:
  - Include the appropriate range of expertise to provide guidance on health effects, developing limit values for validated quantities
  - Ensure sensitive populations get due consideration
- Regulators:
  - Include photobiological safety and glare among the performance specifications required for SSL products
  - Reference appropriate standards and use validated quantities to establish mandatory limits for glare and photobiological safety
  - Energy and equipment regulators should engage with public health authorities to ensure public spaces do not expose sensitive individuals to glare and retinal hazard from SSL.

Design intrinsically safe lighting products

Photobiological Safety

Glare

More careful practices when designing installations and installing products are required

Smart Sustainability in Lighting and Controls SSLC

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The last word...

- Light, an optical radiation, a flux of photons
  - Being elementary particles, photons are all the same!
- Each photon carries its own amount of energy and momentum, which determines its interactions with matter
- Photons are scattered and absorbed by living tissues, producing heat and photochemical reactions, including photodetection (physiological basis of vision)
- **These effects are "technology agnostic"**

THANK YOU

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Solid State Lighting: Review of Health Effects

OCTOBER 2024

Technology Collaboration Programme

Energy Efficient End-use Equipment International Energy Agency

Solid-State Lighting: Review of Health Effects

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