Smart Sustainability in
Lighting and Controls SSLC

Solid-State Lighting: Review of Health Effects

Overview of new Lighting and Health report

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The new IEA 4E SSLC report on Lighting and Health

Health:

- Broadly defined according to WHO (1948) definition: Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity. (World Health Organization 1948)

Objectives of this report:

- To study the health impacts on people of solid-state lighting, considering issues that concern both large fractions and small sensitive groups of the population
  - Identify the psychological and physiological processes that light can affect, based on scientific evidence
  - Focus on areas where regulation or consumer advice might help to prevent adverse effects
  - Identify areas where metrics and test methods don’t exist yet
- To provide interpretation and guidance to policy-makers on setting appropriate requirements on health-related metrics for the following solid-state lighting product categories:
  - Lamps and luminaires (both consumer and commercial) for general interior lighting and street lighting, when used as intended in everyday applications
  - Highlighting risks that could emerge if used incorrectly by consumers (where engineering controls don’t apply)
  - Providing guidance relevant to sensitive populations

The new IEA 4E SSLC report on Lighting and Health

This report **does not:**

- Specify lighting design choices that deliver the desired conditions (not a guide to how to do lighting correctly). Focus is on emissions (from products), but with commentary on exposures (products in use)
- Consider exposures happening during manufacturing or installation

Products out of scope:

- Automotive lighting
- Light sources that are not lighting products (e.g., battery powered: toys, portable lamps), displays

Methodology:

Update of first IEA 4E SSL health report (September 2014)

Extensive review of literature published between 2015-2021 (research papers, review papers, collective appraisal reports, international guidelines, standards), augmented by additional relevant documents published between 2021 and 2024.

The publication of the new report is expected in June 2024.

Chapters

Photobiological safety

Discomfort Glare

Temporal Light Modulation

Circadian effects

Acute neurobehavioural effects

Long-term effects (AMD, myopia, cancer)

Photobiological safety

Photobiological safety

- Thermal and photochemical « direct » effects of optical radiations on the skin and the eye:
  - Effects appearing with exposures lasting from less than a second to about 8 hours
- The « blue light hazard » is the only photobiological hazard with the SSL product categories studied in this report
  - Short wavelength visible light (blue, violet) induces cell death in the retina, according to the exposure dose (weighted retinal irradiance by exposure time)
  - Cumulative photochemical reaction
- Standards (IEC 62471, CIE S009) and regulations (EU low-voltage directive and product safety standards) define acceptable « risk groups », typically « no risk » (RG 0) or « low risk » (RG 1) for consumer products.

Photobiological safety

- There is currently no consensus between the lighting community and many retinal experts about the need to revise the current exposure limit to the blue light hazard.
  - A systematic review and update of the blue light hazard exposure limit are recommended in view of the independently published studies that have found retinal damage below the existing limit using modern detection techniques.
- More measurement data is needed to know the emission levels of SSL products emitting below 430 nm, a spectral range where the retina may be significantly more sensitive for some populations, including children.
- Product « risk groups » are currently defined for the general population
  - The risks groups of SSL products intended to be used by sensitive populations (including children) should be assessed using another spectral sensitivity curve
- Research revealed the circadian aspect of retinal photoxicity: the retina is more sensitive at night
  - SSL products used by people exposed at night should be chosen more carefully

Discomfort glare from Solid-State Lighting

Discomfort glare

- Discomfort glare causes discomfort without necessarily impairing the vision of objects.
- It is experienced when the visual field includes luminance contrasts exceeding a certain level defined by the adaptation of the eye.
- Unlike disability glare, discomfort glare is not directly influenced by the absolute quantity of light emitted by the glare source at the eye, but rather by the luminance contrast with the surrounding and with the background. In central vision, discomfort glare is closely dependent on the spatial properties of the glare source, such as the contrast-defining edges.
- The physiological mechanisms contributing to discomfort glare are not fully understood.

Discomfort glare from indoor SSL products

- Large area uniform sources are intrinsically associated with lower luminance levels, and less glare, than small size sources emitting the same luminous flux. Indoor lighting SSL products that have large luminous areas can be assessed using established glare indices such as UGR.
- The non-uniformity of the luminous area of SSL lamps and luminaires is detrimental to discomfort glare. The CIE defined a correction to apply to the UGR index to provide a correct assessment of discomfort glare for non-uniform sources.

Discomfort glare from outdoor SSL products used at night

- In street and road lighting, SSL luminaires do not seem to produce more discomfort glare than luminaires of older technologies.
- Discomfort glare is often investigated from a distance which makes the glaring light source appear very small (point source).
- The effect of the non-uniformity of street and road lighting luminaires is not known. This non-uniformity becomes visible at close distances.

Influence of colour and spectral distribution on discomfort glare

- LEDs emitting a high proportion of short-wavelength light (blue light) cause more discomfort glare than other colours. White LED light with lower CCT values (warm white) are perceived as less glary than with high CCTs (cold white).
- The role of the spectral distribution in discomfort glare cannot be fully explained by the observed correlation between discomfort glare and CCT, as there are infinitely many possible spectral distributions for any given CCT value.
- There is no established model to include the spectral dependency in the assessment of discomfort glare. However, several models are available in the published literature.

Migraines and photophobia associated with discomfort glare

- Empirical evidence of a link between visual discomfort and neural responses
- Glare can trigger and aggravate headaches in people suffering from migraines
- The contribution of visual pathways has been demonstrated:
  - High luminance contrasts
  - Spatial frequency content of the visual field
- Non-visual pathways involve pain receptors and pain modulators responsible for aversive or painful responses to glare in sensitive people (with a possible influence of the spectral distribution of light)

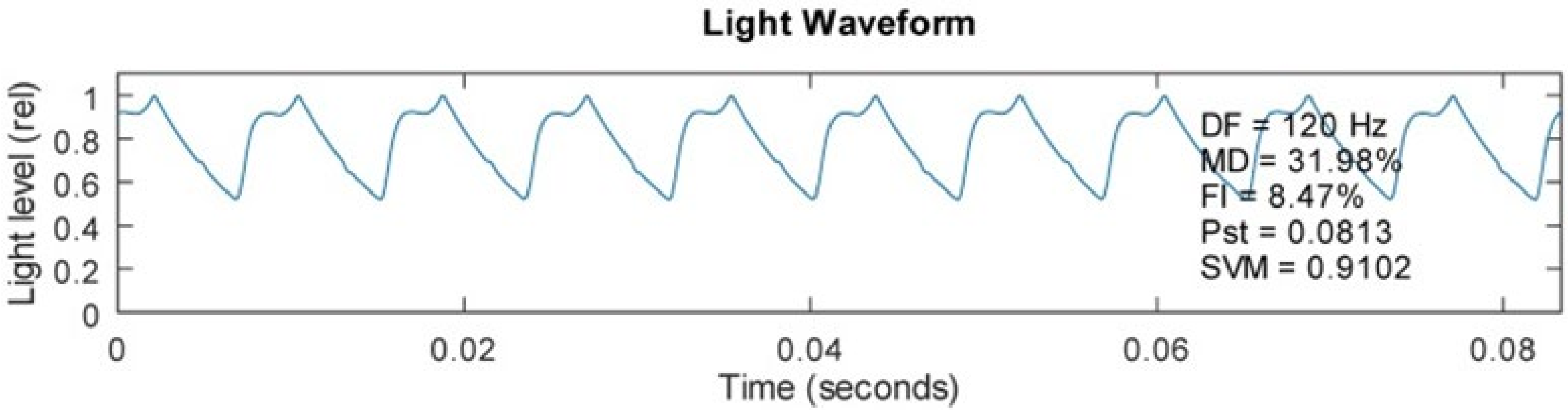
Discomfort glare

- Young people are more sensitive to discomfort glare during short exposure times
- Elderly people may experience a decrease in visual performance after a long exposure to discomfort glare
- Discomfort glare varies with the time of the day (higher in the morning, decreasing along the day). The mechanism is not known yet.

Temporal light modulation

Definition: It's the stimulus!

- Temporal light modulation (TLM): Fluctuation in luminous quantity or spectral distribution of light with respect to time [CIE TN 012:2021].
  - Description: A light stimulus with a waveform that exhibits time-based modulation, characterized with parameters including the frequency, modulation depth, waveform shape, and (for rectangular waves) duty cycle.

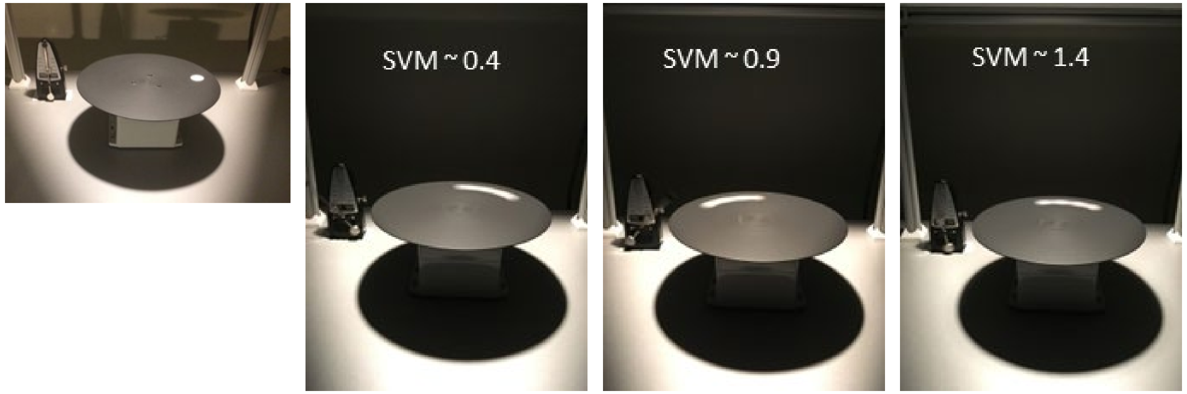


TLM and brain activity

- Photoreceptors detect this luminous variation and pass pulsed signals to the visual cortex
- Some individuals are more sensitive to this than others
  - They detect TLM at higher frequencies, and lower modulation depths, than others
  - Exactly why is not known, but there are diagnostic tests
- This neural noise can make neural computations more difficult, increasing fatigue and contributing to eyestrain
- At the extreme of sensitivity, TLM can cause epileptic seizures or migraine headaches.

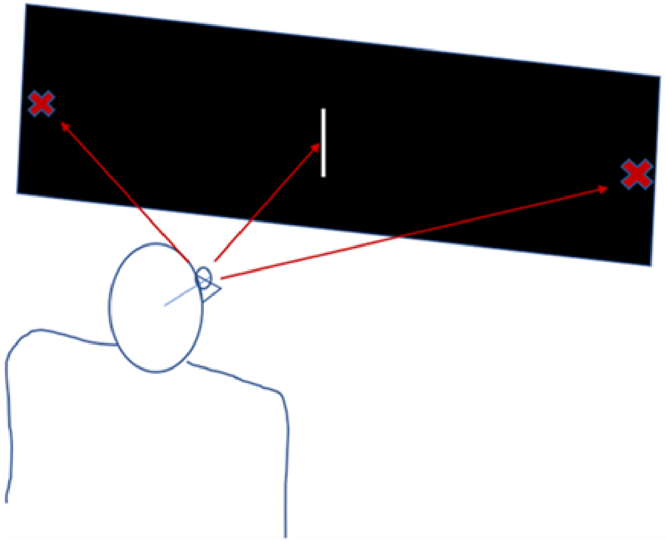
Visual perceptions

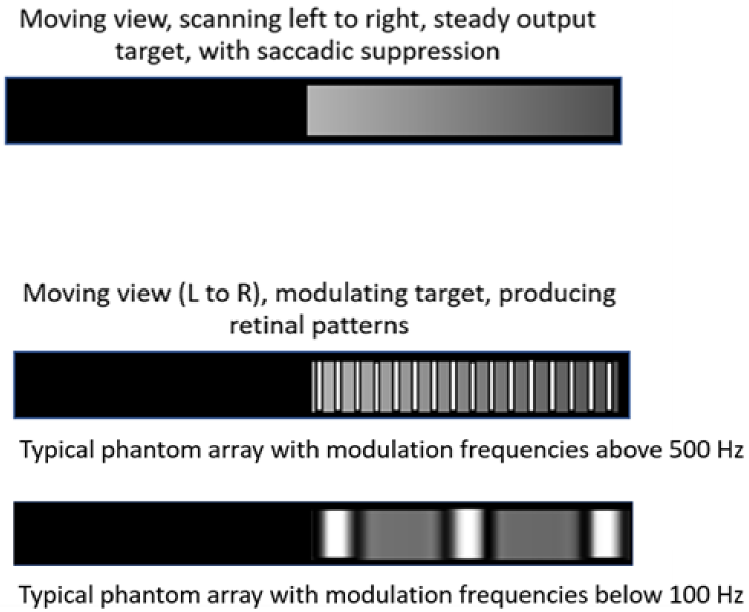
Stroboscopic effect – limited in EU by the *Ecodesign* regulation, SVM ≤ 0.4 the limit as of September 2024



Phantom array effect – no metric yet, therefore, no limit values.

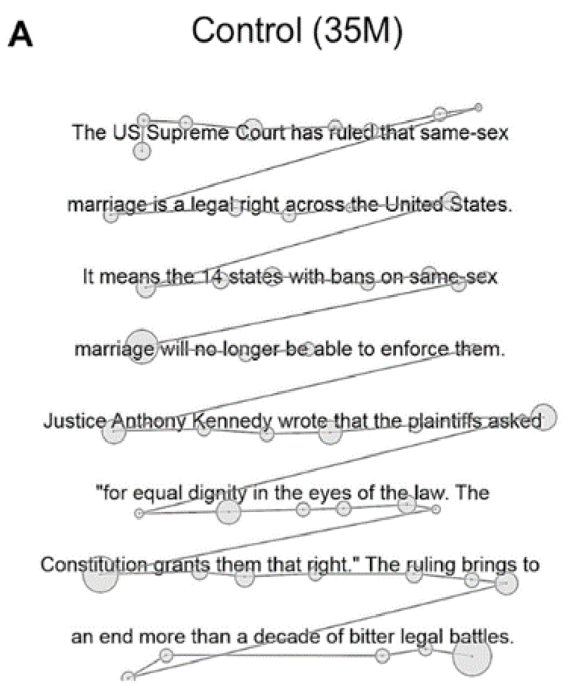
Retinal patterns likely to add neural effort to process the visual image.





TLM and eye movements

- Eye movements are controlled in part by visual information obtained during each saccade. Anything that disrupts eye movements makes neural computation more difficult.
- Wilkins showed in 1986 that TLM from VDTs (50 Hz vs 100 Hz) and fluorescent room lighting (100 Hz vs 20 kHz) disrupted eye movements.
  - In each case, the lower frequency caused larger saccades.
- In reading, longer saccades might mean that more corrective saccades are required, increasing fatigue and slowing performance.



Chen Oh et al. (2018), fig. 7.
https://doi.org/10.1371/journal.pone.0203924.

Recommendations

- Some phenomena aren't yet well understood and lack quantities with which to define limits, but...
- A generally good idea would be to reduce TLM as much as possible to avoid creating conditions that add to neural effort, for everyone and especially for sensitive people (young people, migraineurs, those who have experienced traumatic brain injury...)
- Noting that TLM is not always consciously perceptible, so sensitive people can be exposed to unwanted conditions without warning.

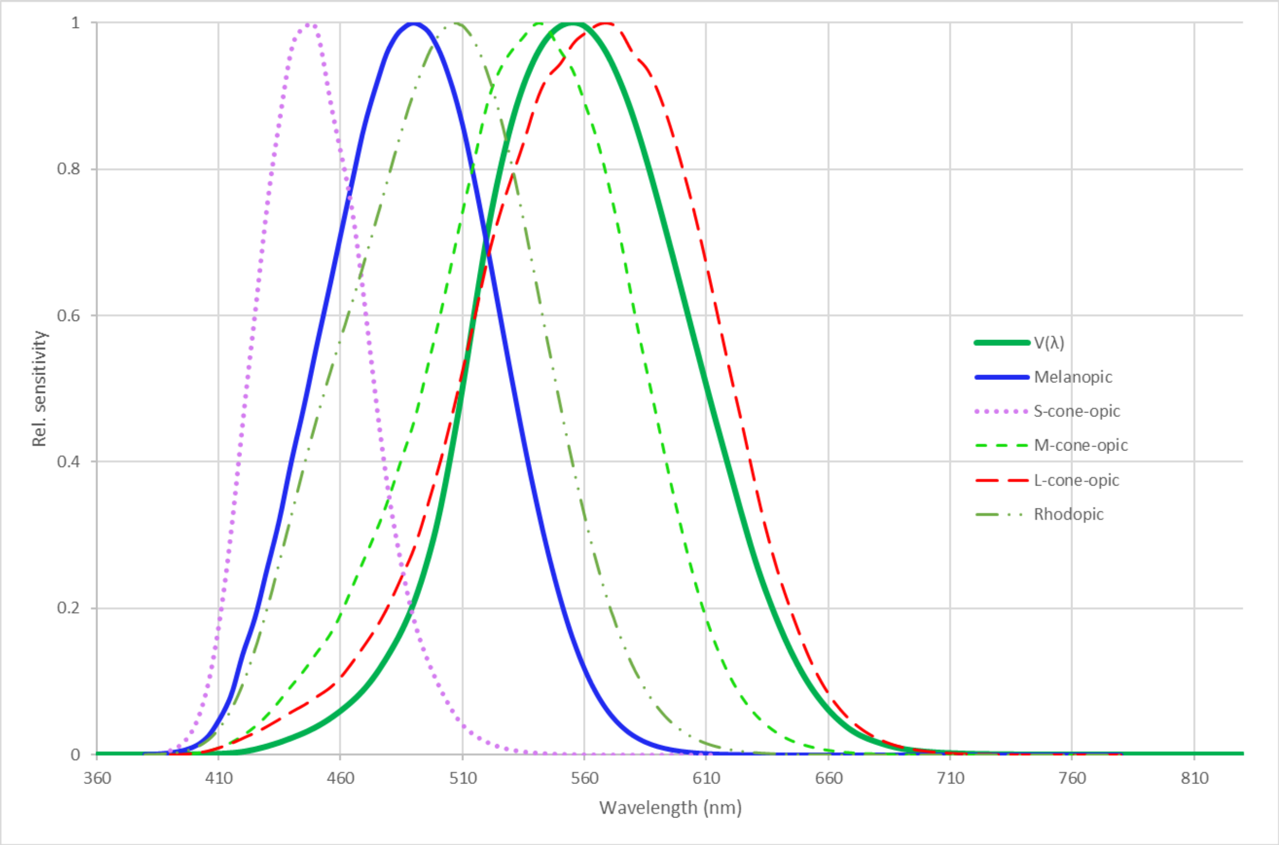
Circadian effects

Circadian Effects - Introduction

- The human internal body clock synchronizes key processes throughout a 24-hour period (i.e., following a circadian rhythm), including sleeping and eating patterns
- Circadian rhythms have a period slightly longer than 24 hours in healthy people and therefore need to be entrained to the 24-hour period by environmental cues, the strongest of which is light
- Entrainment of circadian rhythms by light has important implications for human health, therefore exposure to light at inappropriate times or in insufficient amounts can lead to circadian disruption and dysregulation, impacting sleep patterns, neuroendocrine function and other physiological processes like body temperature and heart rate.

Measuring light exposures

- Specify the photoreceptor & spectral sensitivity
  - *V(λ)* for photopic vision
  - α-opic for cones, rods, ipRGCs (melanopic for ipRGCs)
- Easiest comparisons when scaled to CIE D65 illuminant, expressed as α-opic Equivalent Daylight Illuminance (EDI) in lx
- m-EDI is used to measure melanopic light exposure



Circadian Effects

- Effects of light exposure on the biological clock
  - Artificial lighting can result in disruptions to the circadian system
  - Light exposure in the evening, before the core body temperature minimum delays the circadian clock, while light exposure after the core body temperature minimum, in the morning, advances the circadian clock
- Effects of light exposure on sleep
  - Light exposure in the evening is most disruptive to sleep and is shown to delay sleep, reduce the amount of slow wave ("deep") sleep and reduce self-reported sleep quality
  - The effect of light exposure on circadian rhythms and sleep is also influenced by pre-exposure to light and the amount of daytime light
    - Being exposed to dim light before being exposed to bright light in the evening can result in further delays to the circadian rhythm
    - Alternatively, bright light exposure during the daytime, either through natural sunlight or bright indoor light rich in short wavelength blue light, can reduce the circadian rhythm's sensitivity to light in the evening and improve sleep quality during the night

Circadian Effects

- Effects of light exposure on metabolic functions
  - More research is needed to clarify any link between morning or evening light exposure and heart rate, cardiac function, and body temperature
- Sensitive populations
  - Certain populations, such as older adults, adolescents, and children may have different sensitivity to light compared to the general adult population
    - Older adults may be more sensitive to light due to physiological changes in the elasticity of the iris, degeneration of the retina, and decreased circadian rhythm regulation from reduced melatonin suppression or degeneration of the SCN
    - Adolescents are found to have greater melatonin suppression from blue light compared to adults
    - Consistent evidence has also shown lighting stimuli evokes a stronger melatonin suppression in children compared to adults

Circadian Effects - Conclusions

- Depending on the timing, amount and wavelength, light exposure can lead to circadian disruption and dysregulation, and can impact sleep onset and quality, neuroendocrine function, and other physiological processes
- Light exposure in the evening delays the circadian clock, while light exposure in the morning advances the circadian clock
- For sleep, light exposure in the evening is the most disruptive and can delay sleep and reduce sleep quality, but these effects are also partially mediated by daytime light exposure, making the relationship between light exposure and sleep somewhat complex

Circadian Effects - Recommendations

- The non-visual system is most sensitive to short wavelengths of light, thereby opting for light richer in longer wavelengths in the evening will be less influential to the circadian rhythm and can be used to reduce melatonin suppression and improve sleep
- Inversely, using light richer in short wavelengths during the morning and daytime could have beneficial effects by decreasing the sensitivity of the circadian rhythm to light in the evening
- Some populations may require different lighting conditions to optimize their circadian rhythms and sleep. For example,
  - Older adults may require more light during the daytime while children and young adolescents may require less light during the evening
  - Shift workers are another population whose light exposure needs differ to healthy adults working daytime hours, and more research is needed to determine their optimal lighting conditions

Acute neurobehavioural effects

Acute light effects on thinking and feeling

- Direct, immediate effects and indirect, time-delayed effects
- Intrinsically photoreceptive retinal ganglion cells (ipRGCs) thought to be involved
  - Precise neural pathways are still under investigation – ipRGCs are widely connected
  - Photoreceptors interact in as-yet-poorly-understood ways
- Relevant parameters:
  - Intensity
  - Spectrum
  - Duration
  - Timing
  - Temporal pattern
  - and possibly, spatial pattern

Intensity effects

- Many studies! and varied results for daytime exposures
  - Performance and physiological results are inconclusive
  - Lab studies of mood are inconsistent in finding effects
  - Self-reported alertness is consistently higher for higher exposure intensities
  - Melanopic quantities are the best predictors of alertness
- Ecological (real-world) dosimetry studies are growing in number
  - Evidence is mixed, but a few studies find that people with higher overall light exposure by day report more positive mood (and sometimes better night-time sleep)

Spectrum effects

- If we knew which photoreceptor was most important, we could target its sensitivity, and use less energy to get the desired effect.
- Lots of products promote specific spectral power distributions (achievable with LEDs) for this reason.
- Weak evidence suggests that light sources that target the ipRGCs might contribute to higher alertness, performance, or mood.
- But other evidence says that the colour appearance of these sources is not preferred.
- What delivers best overall lighting quality?

Sensitive populations

- Interindividual differences are known to influence responses to light
  - e.g., chronotype, age, culture, light sensitivity
  - but there are too few studies on any one variable for conclusive statements.
- Behaviours also create subgroups – here shift work is a key influence
  - Bright light during the night shift can reduce sleepiness at work, but...
  - Can also suppress melatonin, with adverse consequences for physiology and circadian regulation.

Recommendations 1

- The quantity of the exposure determines the effect (function of intensity and spectrum) – melanopic quantities are the best predictors.
- Brown et al. (2022) developed a single integrated function for melanopic EDI and **both circadian and acute effects**, leading to the first consensus recommendation for daily light and dark exposure:
  - Minimum 250 lx melanopic EDI at the eye during the day
  - Maximum 10 lx melanopic EDI at the eye for 3 hours before bedtime
  - Maximum 1 lx melanopic EDI at the eye during sleep

Recommendations 2

- Achieving 250 lx of melanopic EDI at the eye all day in many interiors with electric lighting only is difficult within existing energy regulations in many places.
  - Design and controls need careful attention here, and integration of daylight and electric light.
- There is a public health component to this message: Individuals can increase their personal light exposure with time in daylight, preferably outdoors.
- Particular attention is needed to increase light exposure of people whose movement is restricted, and who rely more on electric light.

Long term effects

Long-term effects: Cancer

- In vitro studies and animal in vivo studies show that melatonin reduces cancer growth.
- Epidemiological studies of long-time night shift workers and people exposed to light at night show increased cancer risk.
- However, there are alternative hypotheses to explain these findings.
- A high intensity of daytime light exposure might mitigate a less-than-deeply dark night exposure.
- No specific lighting product or system is implicated in cancer risk.

Long-term effects: age-related macular degeneration (AMD)

- Retinal ageing is associated with oxidative stress triggered by chronic light exposures
- The role of long-term light exposure (natural and electric) on the development of AMD is still controversial. It has not been firmly established by all the available epidemiological studies. The meta-analyses of these studies reached conflicting conclusions.
- In the published epidemiological studies, the contribution of the exposure to electric light in the overall exposure could not be assessed. Therefore, it is impossible to conclude on the effect of long-term chronic exposures to SSL products on the development of AMD.

Long-term effects: myopia

- The onset and progression of myopia have been strongly correlated with time spent outdoors during childhood. The light exposure received outdoors is the most significant factor involved in this relationship.
- The shortest wavelengths of the visible spectrum up to 400 nm appear to be involved in the regulation of the growth of the eyeball through several pathways, some of them being mediated by the newly discovered neuropsin. More research is needed.
- Although the current epidemics of myopia and high myopia developed in parallel trends with the integration of LEDs in lighting products and electronic displays, the exposure to LEDs has not been identified as a cause of myopia. The use of computers, smartphones, and tablets, which all incorporate LED backlit displays, was indirectly correlated with myopia through the reduction of time spent outdoors as these objects have been increasingly popular among children.
- Current SSL lighting systems emit very small amounts of light towards the limits of the visible spectrum, i.e., violet, and red lights. Existing general lighting systems cannot provide light exposures comparable to the outdoors in terms of quantity and spectral content.

Conclusion

Three areas where SSL-focused attention is particularly important:

- Further examination of the issues related to the blue light hazard in sensitive populations
- Discomfort risks that arise from the ways in which some SSL products are designed and used. This can be targeted at both the manufacturers (so they don’t make such products) and at consumers (so they don’t put them in their homes).
- Temporal Light Modulation : development of new quantities and establishment of new limit values to reduce risks to individuals. Regulations to further tighten the potential for TLM, especially in products that are dimmed, i.e., apply limits to products **not at full power**.

Useful messages

- “Bright day - dark night” : make the public aware of their personal responsibility in this regard and providing guidance on how to do this.
- Special focus on populations who can’t access daylight, and programs to make their daily light exposure higher and nights darker.
- Making daylight time a required part of every daycare and school day, to prevent myopia (focus on children 8 and under).
- Exploring lighting design, technology, and controls interactions to enable the delivery of higher light exposures by day without unduly increasing energy use for lighting.

Thank you for your attention