Smart Sustainability in
Lighting and Controls SSLC

Solid State Lighting: Review of Health Effects

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Solid-State Lighting: Review of Health Effects

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About the IEA 4E Smart Sustainability in Lighting and Controls (SSLC) Platform

The IEA 4E Solid State Lighting (SSL) Annex was established in 2010 under the framework of the International Energy Agency's Energy Efficient End-use Equipment (4E) Implementing Agreement. Its purpose has been to provide advice to its member countries seeking to promote energy efficient lighting and to implement quality assurance programmes for SSL lighting. In 2024, the SSL Annex renamed itself Smart Sustainability in Lighting and Controls (SSLC) Platform. Member countries and economies participating directly in the work of the SSLC Platform include Australia, Denmark, the European Commission, France, the Republic of Korea, Sweden and the United Kingdom. Information on the IEA 4E SSLC Platform is available from: https://www.iea-4e.org/ssl/

About the International Energy Agency's Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E)

The European Commission and fourteen countries from Asia-Pacific, Europe and North America have joined together under the forum of 4E to share information and transfer experience in order to support good policy development in the field of energy efficient appliances and equipment. 4E focuses on appliances and equipment since this is one of the largest and most rapidly expanding areas of energy consumption. With the growth in global trade in these products, 4E members find that pooling expertise is not only an efficient use of available funds, but results in outcomes that are far more comprehensive and authoritative. Launched in 2008, in view of its achievements during its first 15 years of work, the IEA endorsed 4E's application for a fourth term that will run from 2024 through to 2029. https://www.iea-4e.org/

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Acronyms

AC	Alternating Current
AMD	Age-related Macular Degeneration
ANSES	Agency for Food, Environmental and Occupational Health & Safety (France)
BAUA	Federal Institute for Occupational Safety and Health (Germany)
BLH	Blue Light Hazard
CCT	Correlated Colour Temperature
CFF	Critical Flicker Fusion Frequency
CFL	Compact Fluorescent Lamps
CIE	International Commission on Illumination
cpd	cycles per degree
DC	Direct Current
DER	Daylight efficacy ratio
DNA	Deoxyribonucleic acid
EDI	Equivalent Daylight Illuminance
EEG	Electro-encephalography
EL	Exposure Limit
ERG	Electroretinographic
EU	European Union
fMRI	functional Magnetic Resonance Imaging
FVM	Flicker Visibility Measure
GR	Glare Rating
Hz	Hertz
IARC	International Agency for Research on Cancer
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IES	Illuminating Engineering Society
ipRGC	intrinsically photoreceptive retinal ganglion cell
IR	Infrared Radiation
ISO	International Organisation for Standardisation
LAN	Light At Night
LED	Light Emitting Diode

LER	Luminous Efficacy Ratio
LVSS	Leiden Visual Sensitivity Scale
MMD	Myopic Macular Degeneration
NEMA	National Electrical Manufacturers Association (USA)
NIR	Near-infrared Radiation
NIRS	Near-Infrared Spectroscopy
NTP	National Toxicology Program (USA)
OLED	Organic Light Emitting Diode
PBS	Photobiological Safety
P_{st}^{LM}	Parameter for short-term light modulation
PWM	Pulse-Width Modulation
RPE	Retinal Pigment Epithelium
SCN	suprachiasmatic nucleus
SPD	Spectral Power Distribution
SSL	Solid State Lighting
SSLC	Smart Sustainability in Lighting and Controls
SVM	Stroboscopic Visibility Measure
TI	Threshold Increment
TLM	Temporal Light Modulation
UGR	Unified Glare Rating
UV	Ultraviolet
UVR	Ultraviolet Radiation
VCP	Visual Comfort Probability
VDT	Video Display Terminal
WHO	World Health Organisation

EXECUTIVE SUMMARY

This report addresses the health effects of solid-state lighting (SSL) used for general lighting applications to support policymakers with interpretation and guidance as they consider whether to take action, such as product requirements or public education, on health-related matters. The focus is the health effects on humans , considering issues that concern both large fractions of the population and small sensitive groups of people: acute effects (effects that develop during or immediately following an exposure) of optical radiation on the eye and the skin, discomfort glare, circadian disruptions, neuro-behavioural effects, temporal light modulation (TLM), and long-term effects (effects that build over months or years) including age-related macular degeneration, myopia and cancer risk.

The report generally is a synthesis of reviews with a focus on reviews published within the past decade. Where substantive reviews do not yet exist, the report summarises individual research papers. Research publications were identified by the authors from literature searches covering the period between January 2015 and May 2021. Relevant documents of satisfactory quality published from May 2021 to February 2024 were also included.

The effects of light on health are technology agnostic. Independently of the invention and adoption of SSL, advances in physiology and medicine have contributed to this awareness. Nevertheless, some features of SSL products may pose health risks and could be improved or applied differently to achieve better outcomes in terms of health and well-being.

Although this report is addressed to policymakers in the first instance, it may prove useful to the entire lighting community, including scientists engaged in fundamental and applied lighting research, illuminating engineers, manufacturers, and lighting practitioners. The conclusions and recommendations of this report are summarised below, for each category of health effect.

Health effects and knowledge gaps

- **Effects of optical radiation on the eye and the skin (photobiological safety)**

The general population should not be concerned by potential risks to the skin arising from the use of Light Emitting Diodes (LEDs) in lighting. Only a small number of people suffering from photosensitive syndromes might see an aggravation of their pre-existing conditions triggered by the shortest wavelengths of visible light emitted by LEDs. Patients taking photosensitizing drugs should also be aware of a potential risk.

The effects of short wavelength light on the retina during short-term acute exposure is known as the blue-light hazard. Following the conclusions of several independent studies, we recommend that photobiological safety committees engage in a systematic review and update of the blue light hazard exposure limits. Before this process reaches its conclusions, we do not recommend assessing the photobiological safety of SSL products using more permissive applications standards, such as the IEC 62471-7 standard published in 2023.

Known sensitive populations to the blue light hazard are children, aphakic and pseudophakic subjects (respectively defined as people having no crystalline lens or wearing an artificial lens implant), elderly people and people suffering from preexisting ocular pathologies. These

sensitive populations are not considered by the current photobiological safety standards used to classify lamps and luminaires in different risk groups. SSL products intended to be used by sensitive populations would be more reliably assessed using lower exposure limits and using the aphakic action spectrum defined by International Commission on Non-Ionizing Radiation Protection (ICNIRP).

More data are needed concerning the emission levels of SSL technologies at wavelengths below 430 nm. Knowing these emission levels would enable the assessment of photobiological safety for sensitive populations in a more reliable way, and the determination of how the results differ from the standard assessment based on the sensitivity of the general population. SSL products that might have high emissions in this spectral range could include lamps and luminaires using violet-pumped phosphor-converted white LEDs as well as high-power SSL products used in professional applications. Other examples are SSL lamps and luminaires incorporating blue or violet LEDs used to "enrich" the emitted white light for various purposes such as colour-tuneability or circadian stimulation.

Because retinal sensitivity increases at night, places in which night work happens, and places where people are exposed at night, should be lit with SSL products classified in a lower risk group than places in which there are only daytime activities.

- **Discomfort glare**

Discomfort glare may be experienced very quickly whenever exposed to a light source, irrespective of the lighting technology. It is the most common cause of immediate complaints about lighting.

Because of the small size and the high intensity of LEDs, some SSL products may produce high luminance levels or high luminance contrasts with their environments, causing discomfort glare in some viewing conditions. Large area uniform sources are intrinsically associated with less discomfort glare than small size sources. The non-uniformity of SSL lamps and luminaires is detrimental to discomfort glare, albeit in a predictable manner in indoor conditions. The effect of non-uniform sources outdoors at night has not been extensively studied in situations of proximity between the subject and the luminaire.

The spectral power distribution of light has an influence on discomfort glare. LEDs emitting a high proportion of short wavelength light may cause more discomfort glare than other types of white light, although there is currently no consensus about these variations. Further studies should be undertaken to reach a consensus among researchers.

Future lighting standards should include more accurate ways to predict discomfort glare by considering both the non-uniformity of SSL light source and the spectral distribution of light.

There is limited information about individual differences in sensitivity to discomfort glare. However, discomfort glare should be avoided in the presence of people suffering from migraines and people generally averse to strong lights, as it can trigger and aggravate headaches. The mechanisms linking strong light levels and headaches revealed a possible influence of the spectral distribution of light. Luminaires with a high proportion of short-wavelength light (e.g., those marketed as 'cool white') should be used with care in the presence of sensitive people. Over durations of several hours, discomfort glare is a factor

contributing to eyestrain. The consequence of glare on visual performance in children and other sensitive populations, such as people having eye diseases, should be studied in more detail.

Discomfort glare has been found to change according to the circadian clock, decreasing as the day progresses. The mechanisms explaining this change are not yet known and merit investigation. With additional information, it would also be possible to evaluate (and perhaps to mitigate) the potential for conflict between increased glare sensitivity and the need for a high light exposure at the same time.

- **Temporal light modulation**

Temporal light modulation (TLM) is a property of light sources and lighting systems, which can exhibit fast fluctuations in luminous or chromatic output over time. There is ample evidence that TLM affects human physiology and behaviour, with implications for health and well-being. It causes visual artefacts such as flicker, stroboscopic effects and the phantom array effect, which are detrimental to lighting quality, and degrades visual performance. Beyond vision, TLM disrupts brain activity and eye movements and affects cognitive performance. The increased neural effort required can manifest in eyestrain, headache, and fatigue, particularly over longer periods.

Pulse-width modulation is the most common form of dimming for LED products, and often introduces rectangular wave modulation to the light output. Rectangular waveforms show consistently the most problematic outcomes for observers. Even in the limited jurisdictions that regulate TLM, the requirements do not apply to the performance of products in a dimmed state, as would be necessary to protect the population against adverse effects. Manufacturers should consider reporting TLM parameters over the whole dimming range of their products to inform users, particularly in jurisdictions where it is not mandatorily required.

Although TLM affects everyone, there remains disagreement about the proportion of the population that experiences severe problems. Sensitive individuals might react sooner and/or more intensely, or experience more serious consequences such as migraine and photosensitive epileptic seizures. These individuals have no way to identify whether a given location might expose them to conditions that trigger their adverse effects. By taking steps to reduce the TLM of the light sources or lighting systems, the risk to any individual of unintentional exposure to an adverse condition can be eliminated.

Following the development of improved information about the effects of TLM and the development of validated derived quantities to predict these effects, application-specific standards with limit values should be developed. Regulators could consider referencing these standards to make their application mandatory, as a matter of protecting vulnerable people.

There is a particular research gap with respect to the risk of headache and task performance decrements. This area of research would be most efficient if it focused on sensitive populations to increase statistical power and to determine what range of conditions ought to be permitted.

- **Circadian effects**

Many physiological processes show daily (circadian) rhythms, which are synchronized primarily by a regular daily pattern of light and dark exposure. Exposure assessment is extremely important in evaluating the potential effects of light on circadian regulation. The melanopic EDI (Equivalent Daylight Illuminance) provides an exposure index that can be used for this purpose.

Inappropriate 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 morning advances the circadian clock while light exposure in the evening delays the circadian clock which in turn disrupts sleep. These effects are also partially moderated by daytime light exposure, making the relationship between light exposure and sleep somewhat complex. Effects of light on metabolic functions are less clear, and more research is needed before any conclusions can be drawn. It is important to note that this conclusion largely pertains to healthy, day-active young and working-age adults. The need for a daily pattern of light and dark exposure for all is well established, but there is more to learn about how light exposure affects sensitive populations, such as children, the elderly, or shift workers.

Some populations may require specific lighting conditions to optimise their circadian rhythms and sleep. For instance, older adults may require more light during the daytime while children and young adolescents may require less light during the evening. Research on the effects of light exposure on infants' and children's sleep remains sparse, and given the importance of sleep for development, this constitutes an important future research need. Likewise, more research specifying clear lighting intervention guidelines for older adults and shift workers is needed to provide optimal lighting environments to improve their sleep and strengthen circadian rhythms.

The general recommendation for healthy light exposure patterns is "bright days, dark nights". The only consensus document with criteria for the target exposures in day, evening, and night-time does not address questions of exposure duration. For example, the daytime recommendation is for a minimum exposure of 250 lx melanopic EDI. If electric lighting is the only light source, this is a difficult target to achieve within current energy regulations in most jurisdictions, even with energy-efficient SSL products. Further research is needed to determine whether a shorter duration of exposure at this level might be acceptable. Furthermore, more research is needed to know if there is an equivalency between shorter exposures at a higher level, and longer exposures at a lower level. This question has importance for practice and lighting energy use.

Given that it is well established that a healthy pattern of light and dark every day is necessary for good health, all lighting recommendations should reflect the need to deliver this pattern. Doing so in an energy-efficient manner might involve using a higher proportion of shorter-wavelength light during the day to increase the effective exposure with less energy and emphasising longer wavelengths at a lower intensity in the evening to maintain a lower exposure. The choice of light source spectrum and intensity, however, must balance other lighting goals; lighting recommendations that integrate the various purposes of a lighting installation are to be preferred over documents that target only circadian regulation, or visual performance, etc. For the time being, until further information accrues, the target maintained

daytime illuminance could be set at 250 lx melanopic EDI or higher at the eye; for evening, a maximum of 10 lx melanopic EDI at the eye or less; during sleep, 1 lx melanopic EDI at the eye or less.

For individuals who are active during the day, daylight remains the best source of light exposure since it is available at the right times, with a quantity and a quality adapted to human needs. Electric lighting cannot replace it entirely. Existing general lighting systems cannot provide light exposures comparable to the outdoors in terms of quantity and spectral content.

Unfortunately, some populations cannot access daylight. In their cases, measures should be taken to make their daily light exposure higher and their nights darker. Nursing homes, long-term care facilities, and prisons should implement such measures to help maintain the individual and collective quality of life in their premises. Authorities could consider adapting their service requirements for these institutions to mandate appropriate light exposures for residents.

- **Acute neuro-behavioural effects**

Light exposure can have immediate effects on physiology and behaviour; these are called "acute effects". Experimental investigations of light exposure have shown that self-reported alertness increases with increasing exposure. Light exposures during the evening and night have stronger effects on alertness than those during the day. Melanopic quantities, such as the melanopic EDI, are better predictors of alertness than photopic quantities. One can deliver the same exposure using less energy if one tailors the spectrum to increase the melanopic irradiance, while keeping other parameters in balance. However, it is not possible to conclude that the stimulation of a single type of photoreceptor improves mood or alertness. The data for physiological markers of alertness and cognitive performance effects remain inconsistent.

People who experience a higher overall daily light exposure report better mood and vitality and possibly better social interactions, but it is not clear what the optimal exposure might be.

Although initial results are promising, much remains to be learned about the potential uses of long-wavelength radiation, both in the visible range and the near infrared region. Ultraviolet (UV) exposure might have some benefits for well-being too, but extreme care is needed to balance this against the substantial risks.

- **Long-term effects**

Several studies have revealed phototoxic effects of low doses of blue light on the retina during long-term chronic exposures. However, the role of long-term light exposure on the development of age-related macular degeneration (AMD) remains controversial. It has not been firmly established by all the available epidemiological studies, and meta-analyses of these studies have reached conflicting conclusions. In the published epidemiological studies investigating AMD, the contribution of the exposure to electric light in the overall light exposure could not be assessed. Therefore, it is not possible yet to conclude anything about the effect of long-term chronic exposures to SSL products on the development of AMD.

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, with several aspects in it: the amount of daily light exposure, the timing of this exposure during the day and the spectral distribution of the light.

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, is indirectly correlated with myopia through the reduction of time spent outdoors, as these objects have been increasingly popular among children.

The shortest wavelengths of the visible spectrum 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, sensitive to violet wavelengths. Solid-state lighting products are based on LEDs which do not emit violet light, apart from violet-pump phosphor-converted white LEDs which are used in a very small fraction of lamps and luminaires. No study has investigated the use of such LEDs to prevent myopia or slow its progression. However, enriching the spectral distribution of SSL products by adding any narrow band light to target a single mechanism is potentially problematic as it is likely to produce other unexpected outcomes. In addition, increasing the dose of light delivered to the eye should be investigated considering the balance between benefits and risks involving all the aspects of the light exposure.

The scientific consensus is that cancer risk increases when the individual lacks a strong daily light-dark rhythm. That is, the conditions to avoid are both too little light exposure by day and too much light exposure at night. Several possible mechanisms have been proposed for the increase in cancer risk, and these may differ between cancer subtypes. Among the proposed mechanisms are reduced melatonin secretion, disrupted circadian rhythms, chronic inflammation, and epigenetic changes in the action of various genes (especially those involved in circadian regulation).

The lack of a strong daily rhythm of light and dark can occur among day-active people who spend most of their time indoors without much access to daylight, or whose sleeping environments are not dark. People who work long-term night shifts are a special population, and this working schedule has been identified as a cancer risk factor in itself. It is unclear that light exposure and/or circadian rhythm disruption alone are the causal factors in the cancer risk for night shift workers because several other variables also co-occur for night shifts (e.g., limited access to healthy meals; workplace health risks; social isolation; family-related stressors).

There is no evidence to link any specific lighting technology to cancer risk. The long-term effective dose depends on the intensity of the light, its spectral power distribution, as well as the timing and duration of the light exposures.

Final advice for policymakers

Light exposure triggers a wide variety of physiological and psychological effects on people. People and other organisms are technology agnostic; the effects occur for any light source, although with greater or lesser probability and intensity depending on the characteristics of the light source. SSL has a major benefit for humanity in that it consumes less energy than the legacy light sources it replaces. Looking at the technology as a product class (within which there are better and worse individual products), SSL overall does not pose new health risks to the general population. However, there is a risk that sensitive individuals could be exposed to adverse effects unexpectedly, and regulations could better protect these individuals either by eliminating these conditions (e.g., setting limit values) or through mandatory reporting and labelling.

Most energy regulations focus on reducing energy used for lighting, with the result being a tendency to reduce light levels that can conflict with the growing knowledge about daily light and dark exposure. Resolving this dilemma and setting appropriate regulations to ensure the public has access to the best quality lighting will require collaboration between government departments of energy/environment and health, regulatory agencies that might not have previously collaborated on lighting.

1. Introduction

This report is an update of the 2014 Health Report from the IEA 4E Solid-State Lighting Annex (Zissis & Martinsons, 2014). Knowledge about the complex relationships between light and health has grown considerably grown over the past decade, with many important implications for lighting technology and practice. This update contains considerable new information.

This report addresses the health effects of solid-state lighting (SSL) on people in order to support policymakers with interpretation and guidance as they consider whether to take action, such as product requirements or education, on health-related matters. It is focused on human-related aspects of SSL, considering issues that concern both large fractions of population and small sensitive groups of people. Biological and broader ecological effects of light on other species are not in scope for this report.

The scope of this review encompasses SSL lamps and luminaires used for consumer, commercial and professional applications, in general interior and outdoor lighting. The following product categories are out of scope: automotive lighting, light sources that are not lighting products (e.g., battery powered: toys, portable lamps), luminous signs and displays. The conclusions will address products in the scope of the Task 1 (LED Quality and Performance Requirements) performance tiers, when used as intended in everyday applications.

The focus of the report is on optical radiation emissions from SSL products that are detected by the eye. The design of lighting installations (i.e., lighting design) is not covered. Exposures typical of products in use are considered. Potential risks arising during normal use and foreseeable misuse, where engineering controls do not apply, are highlighted. Risks arising from exposures received during manufacturing or installation are not considered. Guidance is provided to the general population as well as several identified sensitive populations.

This report includes separate sections concerning specific aspects of light and health:

- Photobiological safety (PBS), concerning the direct effects of optical radiation on the skin and ocular tissues
- Glare, including several distinct phenomena responsible for discomfort and decreased visual performance
- Circadian regulation effects including sleep and physiological outcomes
- Acute neuro-behavioural effects
- Temporal light modulation (TLM), referring to fluctuations in the luminous or colour output of lighting products, causing visual and neurophysiological outcomes; and
- Long-term effects including age-related macular degeneration (AMD), myopia, and cancer risk.

Electrical safety and human exposure to electromagnetic fields emitted by lighting devices are out of the scope of this study. These issues are independent of the scope of the SSLC Platform, and they are covered by international and national standards and regulations.

The report generally is a synthesis of reviews with a focus on reviews published within the past decade. Older sources of information were sometimes used to provide a background to each effect category. Where substantive reviews do not yet exist, the report summarizes individual research papers. Research publications were identified by the authors from literature search equations implemented by the experts for the period between January 2015 and May 2021. The search engines used were Scopus and PubMed. The search results were augmented by documents (including research papers) known to the authors. Documents published from May 2021 to February 2024 were also included if they were deemed relevant and of satisfactory quality. The documents included are scientific articles and journals published in English or French in peer-reviewed journals, without prejudging their impact factor. Thus, the raw material for this report includes, both systematic and narrative reviews, meta-analyses, original research papers, collective health appraisal reports, international guidelines, standards, and position papers published by relevant stakeholders. Where this report differs from these reviews is its final goal to establish SSLC Platform guidelines specific to addressing health issues associated with SSL products.

Each section contains specific conclusions and recommendations relevant to the addressed category of effects. General conclusions and recommendations are given at the end of the report. Although this report is addressed to policymakers in the first instance, it may prove useful to the entire lighting community: scientists engaged in fundamental and applied lighting research, illuminating engineers, manufacturers, and lighting practitioners.

2. Photobiological safety

The protection of the skin and the eye against the adverse effects of non-ionizing optical radiation, specifically ultraviolet (UV), visible, and infrared (IR) radiation, is the objective of photobiological safety (PBS). This discipline considers the acute photothermal and photochemical effects resulting from the interactions of incident photons with biological tissues. The typical time scale for the occurrence of the PBS effects varies from less than a second to about 8 hours. For historical reasons, longer term effects of light exposure are not considered in PBS standards and regulations. This is also the case of effects associated with temporal light modulation, as well as circadian effects. These effects are addressed in other sections of this report.

2.1. Effect of light emitted by SSL products on the skin

The deleterious effects of light to the skin essentially appear in the UV range (for example: erythema, carcinogenesis, aging, melanogenesis, etc.). A recent publication revealed that blue light with wavelengths of about 430 nm negatively affects the repair of deoxyribonucleic acid (DNA) in human skin tissue damaged by irradiation to UV-B exposure (Douki, 2024). This study was carried out with blue light exposure levels typical of outdoor sunshine conditions. The results cannot be transposed to levels of blue light from SSL products used in everyday applications for indoor and outdoor general lighting, which are much lower.

With visible and infrared radiation, burns can be induced with very high irradiances. LEDs used in general lighting are currently far from reaching the irradiance levels required to burn the skin (ICNIRP, 2013). Therefore, the general population should not be concerned by potential risks to the skin arising from the use of LEDs in lighting. As it is the case with the very small amount of UV radiation emitted by discharge lamps, such as fluorescent tubes, only a small number of people suffering from photosensitive syndromes might see an aggravation of their pre-existing condition triggered by the shortest wavelengths of visible light emitted by LEDs (blue and violet light). This is the case for instance of people suffering from specific conditions such as lupus. Patients taking photosensitizing drugs should also be aware of a potential risk (ANSES, 2010).

2.2. Background on light absorption by the retina and the blue light hazard

Light is an optical radiation that can be detected by the human eye. Incident light on the eye passes through the cornea, the aqueous humour, the pupil, the crystalline lens, and the vitreous humour before reaching the retina, where it interacts with photosensitive cells. Light falling on the retina is responsible for vision, but it is also a factor of stress. Two types of interactions are responsible for stressing the retina: the photothermal effect, which is the production of heat following light absorption, and photochemical effects, which involve the interaction of photons with organic molecules (SCHEER, 2018).

The photothermal effect may damage the retina following high exposure levels to optical radiation. In the field of lighting, it is a concern with exposures to very powerful sources of light which are not in the scope of this report. This type of retinal damage (burn) is referred to as thermal retinal damage (ICNIRP, 2013).

Photochemical effects are wavelength dependent. The short-wavelength optical radiations, such violet light and blue light, interact with certain molecules of the retina to produce

reactive oxygen species (ROS) which accumulates in retinal cells and are responsible for damages through oxidation reactions, a process called oxidative stress (ANSES, 2010).

The mitochondria of retinal cells are highly susceptible to light-induced oxidative stress as they generate ROS under exposure to short-wavelength light (Alaimo *et al.*, 2019). Blue light induced damage was found in different types of retinal cells, including ganglion cells (Núñez Álvarez and Osborne, 2019), rods and cones (Marie *et al.*, 2020; Miralles de Imperial Ollero, Gallego-Ortega, Norte-Muñoz, *et al.*, 2021), and Müller cells (Di Pierdomenico *et al.*, 2020; Fietz *et al.*, 2023), ultimately leading to cell death above a certain exposure threshold.

The macular pigments of the retina provide a natural protection against oxidative stress because they absorb blue light (ICNIRP, 2020). The retinal pigment epithelium (RPE), the layer of cells nourishing the photoreceptors, also contain melanin, a protective absorbing pigment. The concentration of these pigments decreases with age while another compound called lipofuscin builds up in the RPE (Behar-Cohen *et al.*, 2011). Lipofuscin is strongly sensitive to blue light and is the main factor causing light-induced cell deaths in the RPE (ANSES, 2010). This type of retinal damage (photochemical damage) is referred to as the blue-light hazard (BLH).

2.3. The ICNIRP exposure limit values

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) publishes guidelines to protect humans against the adverse effects of optical radiation. The guidelines covering incoherent radiation can be applied to the light emitted by general lighting devices to assess whether a given exposure is safe for the eye and for the skin. According to the ICNIRP, exposure is safe if it does not exceed the Exposure Limit (EL) value corresponding to the type of hazard considered. The latest ICNIRP guidelines were published in 2013 (ICNIRP, 2013).

The ICNIRP guidelines provide EL values applicable to the BLH. The ICNIRP defines two categories of populations having different sensitivities to the blue light hazard:

- The general population, having healthy eyes. Their sensitivity to the BLH is defined by the B-lambda curve extending between 380 nm and about 550 nm, peaking at 420 nm.
- A sensitive population consisting of children below 2 years old, people with artificial lens implants (pseudo-phakic subjects), and people without crystalline lens (aphakic subjects). Their sensitivity to the BLH is defined by the A-lambda curve extending from 300 nm (UV radiation) to about 550 nm.

The sensitivity functions A and B are used as weighting functions to define the effective exposure dose from the spectral radiance of the light source. A graph showing the two sensitivity curves is available in the report published by the IEA 4E SSL Annex in 2014 (Zissis & Martinsons, 2014).

The BLH-EL value is expressed in terms of a weighted radiance dose for exposure durations less than 10 000 s:

$$D^{EL} = 10^6 \text{ J m}^{-2}\text{sr}^{-1}$$

When the exposure time is greater than 10 000 s, the BLH-EL value is expressed in terms of a weighted radiance:

$$L^{EL} = 100 \text{ W m}^{-2}\text{sr}^{-1}$$

The weighted radiance L^{EL} and radiance dose D^{EL} are evaluated in an angle of acceptance that depends on the exposure duration. The variation of the angle of acceptance is based on the involuntary eye movements involved in normal visual tasks which spread the image of the source on the retina.

The BLH-EL limits defined by the ICNIRP are used in the CIE S009:2002/IEC 62471:2006 photobiological safety standard. This standard was jointly elaborated to classify the light source in different Risk Groups by assessing several potential adverse effects on the eye and the skin following exposure to infrared, visible and UV radiation (Sliney, 2016). In the case of solid-state lighting, which is essentially based on LEDs and OLEDs, the blue light hazard is the most restrictive photobiological hazard considered by these standards.

According to the CIE S009 / IEC 62471 standard, Risk Group 0 is the "Exempt" group for which no photobiological hazard is expected to happen under foreseeable conditions. Risk Group 1 is the "Low risk" group: products are safe for most use applications, except for very prolonged exposures. Risk Group 2 is the "Moderate risk" group: products generally do not pose a realistic optical hazard if the aversion response limits the exposure duration, or when lengthy exposures are unrealistic. Risk Group 3 is the "High risk" group. Products in this category pose a potential hazard even for momentary exposures.

This standard assigns the light sources to a certain Risk Group according to the time it takes to reach the EL values. The definitions of the four Risk Groups are the following:

- Risk Group 0: exposure limit is not exceeded within 10 000 s
- Risk Group 1: exposure limit is not exceeded within 100 s
- Risk Group 2: exposure limit is not exceeded within 0.25 s
- Risk Group 3: exposure limit is exceeded within less than 0.25 s

Following this standard, the exposure to the BLH should be assessed at a viewing distance of 200 mm from the light source. However, for light sources emitting white light, the standard assessment can be performed at a distance where the illuminance is 500 lx. In most instances, the distance of 200 mm corresponds to a higher exposure than the distance at 500 lx. Being more restrictive, the distance of 200 mm is therefore the most widely used by test laboratories to assess the Risk Group of solid-state lighting products.

Several product safety standards are applicable to solid-state lighting products, such as LED modules, LED lamps and LED luminaires. One example is the IEC 60598 standard series (IEC, 2020) covering the thermal, mechanical, electrical, and optical safety of luminaires. These standards define acceptable Risk Groups for each product category. Consumer lamps and luminaires for instance should belong to Risk Groups 0 or 1. Professional luminaires such as street lighting luminaires should belong to Risk Group 0, 1 or 2. In the latter case, a specific safety marking should be printed by the manufacturer. In addition, a safety distance or a safety illuminance level should be given to facilitate the installation in safe conditions for the eyes of the viewers.

In addition to the IEC 62471:2006 standard, the IEC published the IEC 62471-7 standard (IEC, 2023) in June 2023 to provide a new assessment procedure to address the various lighting applications. This new approach is based on revised emission limits related to the intentional

or unintentional direct viewing of the light source as well as assessment distances depending on the considered lighting application. The new emission limits are based on the current exposure limits of the ICNIRP, given in the previous section (D^{EL} = 10^6 J $m^{-2}sr^{-1}$).

The IEC 62471-7 procedure, based on a product- and application-related assessment, leads to a pass/fail result for a specific product in that given application. Four different "blue-light hazard application groups" are defined from the blue light hazard B-lambda weighted radiance (sensitivity curve of the general population) emitted by a product:

- The BLH-A application group corresponds to a blue light hazard radiance between 0 and 10 000 $Wm^{-2}sr^{-1}$. This application group covers both Risk Group 0 and Risk Group 1. Products classified as BLH-A may be safely viewed for 100 s.
- The BLH-B application group includes Risk Group 2 products in the lower range of the blue light hazard radiance, with values between 10 000 and 100 000 $Wm^{-2}sr^{-1}$. Products classified as BLH-B may be safely viewed for 10 s.
- The BLH-C application group includes Risk Group 2 products in the upper range of the blue light hazard radiance, with values between 100 000 and 4 000 000 $Wm^{-2}sr^{-1}$. Products classified as BLH-C may be safely viewed for 0.25 s.
- The BLH-D application group corresponds to Risk Group 3, defined by a blue light hazard radiance greater than 4 000 000 $Wm^{-2}sr^{-1}$. Products classified as BLH-D are not safe to look at.

The IEC 62471-7 defines an assessment distance and an allowable application group for different categories of applications. For instance, the following requirements are listed:

- Luminaires used by children and luminaire used in clinical areas of hospital and health care buildings should be classified as BLH-A assessed at 200 mm.
- Table luminaires, wall luminaires, suspended luminaires for office and home use should be classified BLH-A or BLH-B assessed at 200 mm.
- Ceiling and/or recessed lighting equipment, luminaires for road and street lighting, flood lighting luminaires should be classified as BLH-A or BLH-B assessed at 1 m.
- Stage lighting luminaires should be classified as BLH-A, BLH-B or BLH-C, assessed at 1 m.

When assessing residential lamps and luminaires, the IEC 62471-7 standard is more permissive than the current requirements of the IEC harmonized standards for product safety listed in the EU regulation (Low Voltage Directive 2006/95/EC). At the time of writing, LED lamps and luminaires for home and office lighting should be classified as Risk Group 0 or Risk Group 1, corresponding to a maximum blue light hazard radiance of 10 000 $Wm^{-2}sr^{-1}$ assessed at a distance of 200 mm. This limit is ten times stricter than the IEC 62471-7 requirements which sets the maximum blue light hazard radiance at 100 000 $Wm^{-2}sr^{-1}$.

2.4. Background and rationale for the definition of the BLH exposure limit values

The current blue light hazard exposure limit values are expressed in terms of weighted radiance dose for an exposure ≤ 10 000 s or weighted radiance for an exposure ≥ 10 000 s. These values were derived from the weighted retinal irradiance which caused observable lesions in macaques under acute exposure to blue light during 100 s and 1000 s (Ham and Mueller, 1976; Ham *et al.*, 1979). Using funduscopy, lesions were then observed at retinal irradiance doses of around 20 to 30 Jcm^{-2} at about 440 nm. The observed damages concerned both the RPE cells and the photoreceptor cells.

From these data, the ICNIRP introduced a safety factor of about 10 to define a so-called "basic restriction" of 2.2 J cm^{-2} (joule per square centimetre) at the wavelength of 440 nm for which the highest level of damage was observed (Sliney *et al.*, 2005). This wavelength was defined as the peak wavelength of the curve describing the relative spectral sensitivity to the BLH. For an exposure longer than 10 000 s, the basic restriction was expressed by ICNIRP in terms of retinal irradiance with a value of 0.22 $mWcm^{-2}$.

The conversion of the basic restriction to the BLH-EL values was performed by the ICNIRP using the Gullstrand model of an adult eye having a focal length of 17 mm, a pupil diameter of 3 mm corresponding to a constricted pupil under bright light, and an ocular transmittance of 0.9 (ICNIRP, 2013).

2.5. Overview of the research on photobiological safety published after 2012

The research papers published in the field of the photobiological safety of lighting products after 2012 revealed several aspects that were not present in most papers published during the previous years. These features are detailed in the following subsections.

2.5.1. Use of LEDs as the exposure source in experiments

The widespread and rapid replacement of most lamps and luminaires by products incorporating LEDs started around 2010 and provided an incentive for most research teams to use LEDs to investigate the mechanisms of light-induced retinal damage in biological experiments, both in vivo (see for instance Shang *et al.*, 2017) and in vitro (see for instance Chamorro *et al.*, 2013). Such studies used narrow band LEDs (coloured LEDs) instead of filtered lamps or lasers that were commonly used before the advent of LEDs.

Several teams investigated the issue of ocular damage with solid-state lighting lamps and luminaires working with LEDs emitting white light at illuminance levels found in home or office environments (Hunter *et al.*, 2012; Peng *et al.*, 2012; Song *et al.*, 2012, 2020; Shang *et al.*, 2014, 2017; Xie *et al.*, 2014; Jaadane *et al.*, 2015, 2017, 2020; Miralles de Imperial Ollero, Gallego-Ortega, Norte-Muñoz, *et al.*, 2021; Ziółkowska and Lewczuk, 2022).

2.5.2. Investigation of combined exposure to multiple wavelengths

The use of LEDs has allowed researchers to have more freedom in choosing the spectral distribution of light exposure. Earlier phototoxicity studies used narrow spectral distributions created by filtering broad band sources. Monochromatic lasers were also used, especially to study the blue light hazard. Current research takes advantage of narrow band LEDs to

generate coloured light, as well as broad band white LEDs. Using LEDs, researchers can therefore investigate the influence of radiation at any wavelength in the visible, near IR and UV-A spectral ranges. In addition, many studies are now focused on producing light exposures having similar intensities and spectral distributions as those found in typical indoor and outdoor environments. This implies combining several wavelengths and intensities. Some studies have investigated the effects of two combined wavelengths, typically blue and red, that are not found in environmental exposure. These studies are aimed to investigate the potential opponent effects of long and short wavelengths on the retina (Albarracin *et al.*, 2013; Begum *et al.*, 2013; Fuma *et al.*, 2015; Del Olmo-Aguado, Núñez-Álvarez and Osborne, 2016; Merry *et al.*, 2016; Giménez *et al.*, 2022).

2.5.3. Use of nocturnal and diurnal animal models

Research using rhesus macaques was carried out in the 1970s (Ham and Mueller, 1976; Ham *et al.*, 1979) providing the basis for the current exposure limits defined by the ICNIRP. The use of non-human primates in research has been more restricted since then. Photobiological studies have therefore made increasing use of rats and mice, animals easier to experiment with in research facilities.

As rats are nocturnal animals, their retina exhibits a different structure than human and non-human primates (Verra *et al.*, 2020). The different configuration of the nucleus of their rods is better suited for detecting low light levels. Nocturnal rodents have a lower cone density than primates and lack a macula, the central zone of the retina where the cone density is very high (Point and Beroud, 2019). Rats are also sensitive to radiation in the UV range (Verra *et al.*, 2020).

Some researchers pointed out that diurnal species would provide a better model to study light-induced retinal damage (Point and Beroud, 2019; Verra *et al.*, 2020; Miralles de Imperial Ollero, Gallego-Ortega, Ortín-Martínez, *et al.*, 2021). Squirrels, rabbits, pigs (Haag, Sieber and Heßling, 2021) and lesser-known rodents such as the tree shrew are now being used in retinal research studies (Verra *et al.*, 2020). The retina of these diurnal animals is richer in cones than rats, although most diurnal rodents are dichromats lacking the long wavelength (red) cones.

Diurnal animals are also used in studies of the influence of the circadian rhythm on retinal phototoxicity, as discussed in the next subsection.

2.5.4. Influence of the circadian rhythm on phototoxicity

The circadian rhythm of mammals is controlled by a central biological clock located in the brain and connected to the retina. However, the retina has its own circadian clock associated with an endogenous melatonin synthesis and secretion (McMahon, Iuvone and Tosini, 2014; Felder-Schmittbuhl *et al.*, 2018), regulating the physiology of the eye over the ~24-hour cycle. Some studies were designed to find out whether retinal phototoxicity is influenced by the timing of the light exposure (daytime or nighttime exposure) (Bery *et al.*, 2022).

2.5.5. More sensitive techniques for detecting cellular lesions in the retina

The pioneering research on phototoxicity that was carried out in the 1970s used direct examinations of the retina such as funduscopy (van Norren and Vos, 2016). Electroretinographic (ERG) techniques have been used to record the electrical activity of the

retina in response to light stimuli (Hunter *et al.*, 2012). Severe retinal damage can be detected when ERG signals are reduced. Funduscopy and ERG have low sensitivity. More recent and more sensitive techniques are now used in retinal phototoxicity experiments.

Autofluorescence has been demonstrated to be an efficient method to detect in vivo the bleaching of the retina caused by the photooxidation of lipofuscin and the photochemical disruption of the RPE under exposure to blue light (Hunter *et al.*, 2012).

Histological sections are now routinely performed, allowing to detect and identify by microscopy cell lesions and cell death before being visible by direct examination (Shang *et al.*, 2014). The TUNEL enzymatic labelling technique is commonly used to reveal by fluorescence the fragmentation of DNA causing apoptosis (Lebon *et al.*, 2015). Other recent DNA labelling techniques are used to study cell death by necrosis and autophagy (Jaadane *et al.*, 2015).

2.6. Newly raised photobiological safety issues with SSL products

2.6.1. Can photochemical retinal damage happen below the current exposure limit for the BLH?

The current exposure limit value concerning the BLH was set by the ICNIRP using thresholds of visible damage observed by funduscopy on macaques exposed during 100 s to 1000 s (Ham and Mueller, 1976; Ham *et al.*, 1979). A safety factor of about 10 was applied (Sliney *et al.*, 2005). Since the publication of the original studies of Ham *et al.* in 1976 and 1989, the techniques used to detect phototoxicity have become more sensitive, enabling several research teams to detect cellular death induced by light at retinal irradiance doses below the ICNIRP basic restriction value.

Using autofluorescence imaging on living macaques, Hunter *et al.* detected photochemical damage under the ICNIRP exposure limit, a level that was thought to be safe (Hunter *et al.*, 2012). The authors suggested lowering the BLH-EL values by a factor of 20 to better protect the eye against light induced damage of the RPE. Jaadane *et al.* (2020) detected retinal damages ex vivo on albino rats at retinal irradiance doses 40 times lower than the basic ICNIRP restriction.

A review of retinal phototoxicity experiments and damage thresholds (van Norren and Gorgels, 2011) showed that the retina of nocturnal rodents is about twice as sensitive to the blue light hazard than the retina of primates. In addition, albino animals may be even more sensitive to retinal light damage. Phototoxicity experiments carried out on diurnal animals showed that their retina is significantly more resistant to light-induced damage, in comparison with nocturnal rodents (Verra *et al.*, 2020).

Even when correcting for the higher sensitivity of rats, the damage thresholds observed in (Hunter *et al.*, 2012; Jaadane *et al.*, 2017, 2020) using up-to-date sensitive techniques appear to be lower than the current ICNIRP basic restriction.

Several authors (Touitou and Point, 2020) pointed out several limitations of studies revealing sub-threshold damages: light exposures limited to one month, difficulties in correctly modelling the living eye, as well as the difficulty of extrapolating the results to the human eye. Cougnard-Grégoire *et al.* (2023) mentioned that healing mechanisms in the retina can offset

the damage caused by exposure to LEDs from displays and lighting devices. This assertion is in contradiction with observations of cumulated retinal damage on rats induced by repeated blue light exposures separated by dark periods of 8 hours (Krigel *et al.*, 2016).

At the time of writing, a few case reports were published describing retinal injuries caused by an accidental exposure to visible light emitted by LED devices (Obana *et al.*, 2011; Zhang *et al.*, 2023). These reports revealed macular injuries following involuntary short-term exposure to handheld high intensity LED devices which are not used as general lighting products. The case report of Obana mentioned that the subject received two exposures separated by a period of 24 hours. Each retinal exposure dose was estimated to be slightly below the ICNIRP exposure limit.

The European Scientific Committee on Health, Environmental and Emerging Risks (SCHEER) concluded in their 2018 report (SCHEER, 2018) that there was no evidence of photobiological risk posed by LED lamps and luminaires of risk groups 0 and 1 under normal conditions of use, i.e., below the ICNIRP exposure limits up to 10 000 s of continuous viewing.

In 2019, the International Commission on Illumination (CIE) published a Position Statement (CIE, 2019) expressing its opinion that the blue-light hazard is not an issue with white light sources used in lighting systems for the general population.

In 2020, the ICNIRP published an opinion (ICNIRP, 2020) concerning the photobiological safety of LEDs, emphasizing the fact that acute damage to the human retina from typical exposures to blue or white LEDs has not been demonstrated.

In 2020, the French health agency ANSES called for a revision of the current BLH-EL values which would consider the results of research investigating sub-threshold retinal damage (ANSES, 2020)

2.6.2. What are the sensitive populations to the BLH?

Several categories of sensitive population were identified by the literature search: children, the ageing population, people with an artificial lens implanted after a cataract, and people suffering from a retinal disease.

In comparison with the adult eye, the child eye has two distinct features to consider for the blue light hazard: its small size and the high transparency of its crystalline lens.

Point (2018) studied the geometry of a newborn infant eye using previously published data on focal length and pupil size. The focal length was shorter, and the pupil was slightly larger than the values considered by ICNIRP to define exposure limits for the adult eye. Considering these values, the retinal illuminance was found to be 2.8 times higher than for the adult eye for the same source luminance.

Growth of the eye not only occurs during the first two years after birth. The eyes continue to elongate for several years, slowing exponentially to reach mature size after the age of 13 years (Fledelius, Christensen and Fledelius, 2014).

The crystalline lens absorbs UV and infrared radiation, and a smaller fraction of visible light. The absorption changes gradually with age. With increasing age, the concentration of yellow

filters in the lens increases resulting in more and more blue light absorption (Behar-Cohen *et al.*, 2011). In children younger than 9 years-old, more than 65% of blue light is transmitted to the retina, in comparison with 20 % to 50% in the case of adults.

The blue light reaching the retina decreases with age. However, lipofuscin accumulates with age, potentially making older adults more susceptible to blue light damage (Hunter *et al.*, 2012). The combined influence of these two antagonistic factors has not been studied. However, several epidemiological studies, such as the European Eye study, suggested that blue light may be more damaging with increasing age (Fletcher *et al.*, 2008; Hunter *et al.*, 2012).

The protective filtering effect of the crystalline lens is absent in aphakic (no lens) and pseudophakic people (people having an intraocular lens implant). This population is more sensitive to the blue light hazard which, in this case, is not limited to blue light but extends to UV radiation, as described by the aphakic action spectrum A-lambda defined by the ICNIRP (ICNIRP, 2013).

People suffering from a wide range of retinal diseases such as different forms of macular dystrophy, AMD, retinitis pigmentosa, glaucoma, are more sensitive to light in general and to the blue light hazard (Arnault *et al.*, 2013).

2.6.3. Can exposure to LEDs during the night be more harmful than during the day?

In rats, visual sensitivity and light-induced retinal damage were shown to be dependent on the circadian rhythm (Organisciak and Vaughan, 2010; Felder-Schmittbuhl *et al.*, 2018). With diurnal rodents, exposure to light during the circadian night induced strong perturbations in retinal functions (Verra *et al.*, 2020) such as retinal clock gene expression, phototransduction, and phagocytosis. Circadian fluctuations of the concentrations of photopigments were also observed on different animal models, implying a modulation of visual responses (McMahon, Iuvone and Tosini, 2014).

2.6.4. Is there a protective effect of long wavelength light on the retina?

The protective effects of exposures at low levels of red light and near-infrared radiation, a procedure called photobiomodulation, were demonstrated in mice and rats. These exposures improved the efficiency of retinal healing processes (Begum *et al.*, 2013) by reducing the effects of oxidative stress (Albarracin *et al.*, 2013).

A study carried out in vitro on human RPE cells showed that the exposure to red light emitted by LEDs at 670 nm resulted in a beneficial increase in phagocytosis of light-induced deteriorated photoreceptor outer segments. Another study carried out in vivo on human subjects suffering from dry AMD showed that wavelengths above 600 nm modified the mitochondrial activity of cells and reduced the oxidative stress induced by other wavelengths (Merry *et al.*, 2016).

These studies suggest that the phototoxicity of blue light can be attenuated by post exposures to long wavelength light (red or near-infrared). It is not known whether simultaneous exposure to blue light above the retinal damage threshold combined with red light or near-infrared radiation is less critical than the exposure to blue light alone.

The lack of near-infrared radiation and the low amount of red light emitted by most white light LEDs used in SSL products was pointed out by some authors (Torriglia, 2018) and by the ANSES (2010) as a possible factor for increasing the risk of photochemical retinal damage with short wavelength light.

2.6.5. Product emission data

Several measurement campaigns investigating blue light emitted by SSL products and their photobiological safety were reported in the published literature. Three types of measurements were reported:

- Some authors investigated the spectral distribution of the emitted light to investigate the relative proportion of light contributing to the blue light hazard (B-lambda weighted measurements).

- Other reports reported the B-lambda weighted radiance, which directly relates to the ICNIRP exposure limit and enables the calculation of the exposure time needed to exceed this limit at a given distance.

- Other authors reported the risk group classifications of SSL products made according to the CIE S009 / IEC 62471 photobiological safety standards (CIE/IEC, 2002/2006).

The study published by James *et al.* (2017) reported several emission measurements to assess the photobiological safety of ten LED lamps used in general lighting application and two 100 W incandescent lamps for comparison of the results. Half of the tested lamps had a built-in diffuser while the other half included bare LEDs. All lamp samples were evaluated in accordance with procedures specified in the standards for photobiological safety of lamps and lamp systems. The procedures are similar to those defined by the CIE and IEC in their joint international standard (CIE/IEC, 2002/2006). The blue-light hazard was considered as the most restrictive for the risk evaluation of these lamps. The measurements indicated that the tested lamps posed no risk. The classification was Risk Group 0 (no risk) when evaluated at distances corresponding to 500 lx illuminance, a condition measurement listed in the photobiological safety standards in the case of general lighting applications. The assessment distances at 500 lx varied between 31 cm for the dimmest lamp and 353 cm for the brightest lamp. The blue light hazard-weighted radiance of LED lamps incorporating a diffuser was about half of that of LED lamps built with bare LEDs. When evaluated at a distance of 200 mm, the general measurement distance recommended in the photobiological safety standards, the 100 W incandescent lamp was classified in Risk Group 1 (low risk), while the most powerful LED lamp (a lantern with partially visible LEDs, without diffuser) was classified in Risk Group 2 (moderate risk).

Dain (2020) and Heßling *et al.* (2019) both reported that warm-white LEDs, compact fluorescent lamps (CFLs) and halogen lamps with comparable correlated colour temperature (CCT) emitted very similar relative doses of blue light (B-lambda weighted). However, some cold-white LEDs were found to emit a relative proportion of blue light of more than twice as high as their respective reference warm-white halogen lamps. These measurements showed that the lighting technology is not a determinant of the relative dose of blue light. As the CCT increases, the relative blue light dose emitted by SSL products increased in similar proportion as with fluorescent lamps. This conclusion was also mentioned by the CIE (2019). It is

consistent with measurements published by ANSES (2010) which showed a strong positive, but non-linear, correlation between the CCT and the B-lambda weighted relative proportion of blue light.

O'Hagan *et al.* (2016) compared the weighted radiances of an incandescent lamp, two LED domestic lamps, one CFL lamp and a 600 mm square LED ceiling luminaire intended for office lighting. The tested domestic lamps reached a weighted radiance dose of about 10% to 20% of the ICNIRP exposure limit, assuming intentional long-term viewing longer than 10 000 s (about 3 hours). The incandescent lamp was towards the middle of the range (14%). The ceiling luminaire had a weighted radiance dose of 1.7% of the blue light exposure limit. As the exposure limit was not exceeded within 10 000 s of continuous exposure, all the tested lamps could be classified in the Risk Group 0,

Leccese *et al.* (2015) studied a sample of LED tubes commercially available to replace T8 fluorescent tubes. A total of 48 fluorescent tubes and 48 LED tubes were included in the study, with an equal distribution among three different CCT values (3000 K, 4000 K and 6000 K). The weighted radiance of each tube was measured at a distance of 20 cm. A comparative analysis was done between LED tubes and fluorescent tubes of the same CCT. At 6000 K and 3000 K, LED tubes had a mean weighted radiance of more than twice as high as with fluorescent tubes. However, at 4000 K, the mean of the weighted radiance of LED tubes was slightly less than with fluorescent tubes. The authors also determined the photobiological risk group of the tested lamps. All LED tubes were classified as Risk Group 0 (no risk), except for one LED tube with a nominal CCT of 6000 K which was classified in Risk Group 1 (low risk). Fluorescent tubes were of 3000 K were all classified as Risk Group 0. Fluorescent tubes at 4000 K and 6000 K were classified in Risk Group 1. A Risk Group 1 classification means that the ICNIRP exposure value is exceeded for a continuous exposure between 100 s and 10 000 s at the distance of 20 cm.

Necz *et al.* (2014) measured the blue light emissions of 19 types of CFLs, 11 types of halogen lamps, and 4 types of LED lamps at the distance of 20 cm. The light sources had very different luminous flux values, between 50 lm and about 1900 lm. All the tested lamps were classified in the Risk Group 0. The tested halogen lamps with a luminous flux greater than 800 lm had a higher blue-light weighted radiance than the CFL and halogen lamps with similar luminous fluxes. This study did not report the CCT of the tested lamps.

The ANSES reported the result of measurements carried out on SSL consumer lamps in a report(ANSES, 2019). Three types of colour-tuneable LED lamps (used at their maximum intensity) and two directional LED lamps were tested. One colour-tuneable LED lamp was tested in two modes: white light with the highest CCT and pure blue setting. This lamp was classified in the Risk Group 0 with the white light setting and in Risk Group 1 with the blue light setting. The two other tuneable lamps were tested in the highest CCT mode. They were classified in Risk Group 1. The two directional LED lamps were also classified in Risk Group 1.

A report published in 2013 by the German Federal Institute for Occupational Safety and Health (BAUA) (Udovicic *et al.*, 2013) reported the results of measurements carried out on bare LED components used in SSL products. Most blue LEDs, used in decorative SSL products, were classified in Risk Group 2 (moderate risk) and associated with maximum permissible exposures as short as 10 s when viewed at a distance of 20 cm (direct viewing conditions).

About half of the tested cold-white LEDs were classified in Risk Group 2 with maximum permissible exposures between 15 s and 70 s. The other half of the tested cold-white LEDs were classified in Risk Group 1. The tested warm-white LEDs were classified in Risk Group 0 and Risk Group 1.

In an article published in 2019 , Bullough *et al.* (2019) investigated the emission levels of three white LEDs at 3000K, 4000K and 6500 K, a blue LED with an emission peak at 450 nm and tested at power levels of 0.5 W and 3 W, a fluorescent T8 tube with a CCT of 4100 K, and an unspecified clear incandescent lamp. These light sources were assessed using a viewing distance of 0.5 m. The LEDs were tested as bare components, without any beam attenuating or shaping device. The results showed that the three white LEDs (CCT of 3000 K) could be classified in Risk Group 1 (low risk). Their respective maximum permissible exposure time lay between 20 minutes for the LED at 6500 K and 43 minutes for the LED at 3000 K. The blue LED tested at a power level of 0.5 W was also classified in Risk Group 1 with a maximum permissible exposure of 6.4 minutes. However, at a power of 3 W, the blue LED was classified in Risk Group 2 (moderate risk) with a permissible exposure of 1.1 minute. The assessment of the clear incandescent lamp led to a Risk Group 1 classification with a maximum permissible exposure of 20 minutes. The fluorescent lamp had a Risk Group 0 classification (no risk) corresponding to a maximum permissible exposure of 50 hours.

Bullough *et al.* (2019) also assessed the viewing of the clear blue sky which led to a maximum permissible exposure of 44 hours, only considering the blue light hazard. At the other extreme of natural light, the authors assessed the exposure to the direct sun in a single arbitrary viewing condition. They found a maximum permissible exposure of about 1 s, only considering the blue light hazard.

Bullough *et al.* (2019) also carried emission measurement weighted by the aphakic action spectrum (A-lambda) defined by the ICNIRP for several sensitive populations. The assessment of the tested white and blue LEDs, the incandescent lamp, and the fluorescent tube, led to null or slight reductions of the maximum permissible exposure. In the case of the blue sky and the sun, there was a significant reduction of the maximum permissible exposure time (down to 8 hours for the blue sky and about 0.4 s for the sun). These results show that the shortest wavelengths of the visible spectrum (below 440 nm) have a significant impact on the photobiological safety assessment when considering the A-lambda action spectrum, which is recommended by the ICNIRP for aphakic and pseudophakic people, as well as children below 2 years of age.

The ANSES (2019) published emission measurements of a violet LED incorporated in a toy (peak wavelength of 403 nm). When the B-lambda weighting was applied, as recommended in the photobiological safety standards CIE S009 and IEC 62471, the assessment led to a classification in Risk Group 0 (no risk). When the A-lambda weighting was applied, a procedure not included in the CIE S009:2002/IEC 62471:2006 standard, the assessment led to a classification in Risk Group 2 (moderate risk) with a maximum permissible exposure of 35 s at a distance of 20 cm.

2.7. Conclusions

2.7.1. Conclusions on the current exposure limits to the blue-light hazard

The ICNIRP blue light hazard exposure limit was established from results obtained by a single team more than 40 years ago using low sensitivity detection techniques and exposures not exceeding 1000 s (about 17 minutes). Since 2012, several independent teams have found retinal damage well below the ICNIRP exposure limit using more sensitive detection techniques and different animal models, including rats but also living macaques. The transposition of these results to the living human eye is uncertain. There is currently no consensus between the lighting community and many retinal experts about the need to revise the current ICNIRP exposure limit to the blue light hazard.

2.7.2. Conclusions on sensitive populations to the blue-light hazard

The higher sensitivity to the blue light hazard is well-established in children, elderly people, aphakic and pseudophakic people, as well as people suffering from retinal diseases.

The current ICNIRP guidelines recommend the use of the aphakic action spectrum to study the retinal exposure of the aphakic and pseudophakic people, and infants below 2 years of age.

The current photobiological safety standards CIE S009 (CIE, 2002) and IEC 62471 (IEC, 2006) do not consider sensitive populations to determine the risk group of lighting products.

2.7.3. Conclusion on circadian aspects of retinal phototoxicity

Based on experimental results obtained on diurnal and nocturnal mammals, the retinal damages induced by light exposure in humans are believed to depend on the circadian time. The observed injuries are exacerbated during the circadian night. Therefore, the exposure to blue light from light sources including SSL products may be more critical at night, rather than during the day.

2.7.4. Conclusion on the protective effect of long wavelength light against retinal phototoxicity

It is not possible to conclude to the existence of a protective effect of red or near-infrared radiation against the retinal toxicity of a white light source such as an SSL lamp or luminaire.

There is no study supporting the assumption that white light sources emitting lower amounts of long wavelength radiation could be more toxic for the retina at the same level of blue light.

2.7.5. Conclusions on emission data measured on SSL products

Several emission measurements were published in articles and reports that were identified using our search strategy. The tested domestic and office lighting SSL products were all classified in Risk Group 0 (no risk) or in Risk Group 1 (low risk), like older technologies of domestic lamps and office lighting luminaires (halogen and fluorescent lamps). As the CCT increases, the relative fraction of blue light emitted by SSL products increased in similar proportion as with fluorescent lamps or halogen lamps. The blue light hazard weighted radiances of the tested SSL products were comparable with levels measured in halogen and fluorescent lamps of similar CCT. This conclusion is consistent with the current IEC product

safety standards which have included photobiological safety requirements to limit the risk groups of domestic and office lighting products to Risk Group 1 assessed at 200 mm.

The measurements carried out on bare LEDs (sometimes visible in some older types of lamps and luminaires) yielded much higher blue light weighted radiance values. Cold-white LEDs were found to be classified in Risk Group 2 and Risk Group 1, with maximum permissible exposure as short as 15 s for one tested component. LEDs emitting blue light, not used in general SSL products, were classified in Risk Group 2 and Risk Group 1, with a maximum permissible exposure of 10 s for one tested component. These results are consistent with older measurements carried out on bare LEDs published by ANSES (2010).

The potentially high levels of blue light weighted radiance emitted at short distances by bare LED components emphasize the importance of the optical design of indoor SSL lamps and luminaires that should prevent direct viewing of the bare LEDs at close range. In doing so, the risk groups of indoor SSL lamps and luminaires were found to be comparable with other lighting technologies.

Some professional SSL products may belong to RG2. In street lighting, sport lighting and industrial lighting, high power SSL products are used. No measurement data were found in these product categories.

2.8. Recommendations

2.8.1. Recommendations on the current exposure limits for 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.

2.8.2. Recommendations on sensitive populations to the blue-light hazard

It is recommended to assess the photobiological safety of lighting products, including SSL products, using the aphakic action spectrum in a wider range of sensitive populations, including children and adolescents, elderly people and people having abnormal retinal conditions.
The risks groups of SSL products intended to be used by sensitive populations should be assessed using the aphakic action spectrum.

2.8.3. Recommendation on circadian aspects of retinal phototoxicity

The photobiological safety of SSL products used by people exposed at night should be considered more carefully than in the case of daytime exposures, especially with people who cannot avoid the presence of light sources in their field of view for a significant nocturnal period. This situation is common in the case of immobile persons in supine position, especially infants, and other sensitive populations. In such situations, SSL products with no risk, such as Risk Group 0 (No Risk), should be used, instead of products classified as low risk or moderate risk.

2.8.4. Recommendation on the protective effect of long wavelength light against retinal phototoxicity

The benefits of enriching the spectral distribution of SSL products using red and near-infrared for alleviating the blue light hazard have not been conclusively demonstrated. Further research is needed.

2.8.5. Recommendations on emission data measured on SSL products

More measurement data are needed to know the risk levels of SSL technologies emitting below 430 nm, a spectral range where the blue light hazard radiance assessed using the BLH action spectrum of sensitive populations (A-lambda) is significantly higher than in the case of the general population (B-lambda action spectrum). A graph showing the two sensitivity curves is available in the report published by the IEA 4E SSL Annex in 2014 (Zissis & Martinsons, 2014).

This is the case, for instance, of lamps and luminaires using violet-pumped phosphor converted white LEDs. Other examples concern SSL lamps and luminaires incorporating blue or violet LEDs used to “enrich” the emitted white light for various purposes such as colour-tuneability or circadian stimulation. The measurements of blue LEDs that were published showed that they may belong to Risk Group 2 (moderate risk), a classification that should not be used in domestic or office lighting according to the current product safety standards.

More data are also needed for high power SSL products used in professional applications such as street lighting, sport lighting and industrial lighting. According to the current product safety standards, these products may belong to Risk Group 2. In this case, they should bear a safety mark and an indication of the safe viewing level, expressed in terms of a threshold illuminance or a threshold distance. It is recommended to assess if these indications are compatible with the intended applications.

2.8.6. Recommendations on using shaded or diffused SSL products

SSL products used at short viewing distance should be shaded or diffused to lower the blue light hazard radiance down to risk exempt levels.

3. Glare

3.1. Definition of glare

The CIE defines glare as being a condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme luminance contrasts (CIE, 2020). A glare source is one that is excessively bright compared with its surroundings and leads to visual impairment and visual discomfort (CIE, 2021).

The CIE makes the distinction between disability glare which reduces visual performance and discomfort glare which makes the observer feel uncomfortable without causing a reduction in their visual performance.

In addition to discomfort and disability glare, Boyce (2014) described distinct phenomena also categorized as glare:

- Adaptation glare: when the light level abruptly changes, the visual system needs some time to readjust to the new ambient light level. This is the case when moving from indoors to outdoors.

- Saturation glare, or dazzle: a painful experience usually felt outdoors when a large part of the visual field is too bright. An example is the diffuse reflection of the sun on snow or water. In this case, light levels at the eye exceeds the maximum level allowed for vision.

The persistent vision of afterimages following the exposure to a bright source can also be considered as a form of glare (ANSES, 2019). Afterimages may persist for seconds or minutes after the initial exposure has ceased. The recovery is longer with older people.

There are numerous well-known safety consequences associated with visual impairment caused by glare phenomena: tripping hazards, falls, vehicle accidents, occupational hazards, etc. The degree of severity of these outcomes varies from inconsequential to lethal.

Glare can be direct, when the light source is in the field of view, or indirect with surface reflections (reflected glare). The following sections mainly deal with direct glare.

3.2. Background of disability glare

Disability glare happens when one or several light sources have a much higher luminance than the rest of the field of view. The high luminance source generates a diffusion halo, caused by light scattering in the cornea, the crystalline lens and in the retina (Vos and Boogaard, 1963; Vos and Bouman, 1964). The diffusion halo is seen as a veil covering the field of view, reducing luminance contrast, and consequently lowering visibility of objects. Dimmer objects can be completely masked by the diffusion veil.

Disability glare can be predicted using well established empirical models of the veiling luminance (CIE, 2002). According to the CIE General Disability Glare model, the veiling luminance depends on several factors:

- Light source characteristics: luminance and size. The colour and spectral distribution are not considered by current models. Their influence is believed to be negligible (Boyce, 2014).
- Viewing conditions: distance to the glare source and position in the field of view. The veiling luminance is proportional to the illuminance at the eye, which depends on the distance through the inverse square law. The veiling luminance is inversely proportional to the square of the apparent angle between the light source and the centre of the visual field.
- The observer: age of the observer (the ocular media become more scattering with age), and pigmentation of their iris (light-coloured irises transmit a greater amount of diffused light inside the eye). In the CIE model, the age factor appears to the power of 4.

From the value of the veiling luminance, several indices were defined to quantify the loss of visual performance associated with disability glare. The threshold increment (TI) is specific to road lighting and applicable to vehicle drivers. The Glare Rating (GR) is used in sport lighting installations to quantify disability glare felt by people in outdoor facilities such as football fields, stadiums, etc.

It is worth mentioning that the models used to predict disability glare are only applicable to outdoor environments at night, where the veiling phenomenon is very likely to be experienced with vehicle headlamps and road lighting for instance. In bright environments, light is similarly scattered by the eye media, but the resulting veiling luminance is usually much less than the adaptation luminance, making disability glare rarely noticed. During daytime, disability glare happens when looking at the sun, directly or indirectly, with reflections on shiny surfaces.

3.3. Background of discomfort glare

Disability glare reduces visual performance but does not necessarily produce discomfort. On the contrary, 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 (Bargary *et al.*, 2015).

The physiological mechanisms contributing to discomfort glare are not fully understood (Boyce, 2014). The psychological aspects of perceived discomfort have been traditionally assessed using subjective evaluations. Psychophysical methods, such as category rating based on psychometric scales such as the De Boer scale, a 9-point scale from "just noticeable glare" to "unbearable", have been extensively used. The methods of evaluation of discomfort glare were reviewed in recent years (Allan *et al.*, 2019; Fotios and Kent, 2021). These reviews presented evidence demonstrating that some aspects of these procedures influence the subjective evaluation, potentially creating bias and reducing the reliability and validity of the results (Fotios and Kent, 2021). The lack of consensus on psychometric scales (Allan *et al.,*

2019) greatly limits the comparability of results from multiple studies and complexify the identification of lighting features influencing the judgment of lighting quality and satisfaction.

Discomfort glare indices have been defined to predict the judgement of an average observer under some given viewing conditions, geometries, and luminance contrasts in the visual field. The discomfort glare formulas often incorporate a logarithm function applied to a physical stimulus, such as a weighted luminance contrast, to model the discomfort sensation, in the spirit of the Fechner's law (Girard *et al.*, 2022).

The Unified Glare Rating (UGR, or quantity symbol R_{UG}) is the discomfort glare index recommended by the CIE for indoor lighting (CIE, 1995). The formula used to compute UGR includes the luminance, apparent size, and position of the light sources in the field of view, as well as the background luminance.

The UGR is applicable to a lighting installation at the room level and was developed using large luminaires with uniform luminance. Nevertheless, lighting manufacturers may assign a UGR value to their luminaires to facilitate their choice in buildings with many identical rooms, such as office buildings and schools for instance. In this case, the CIE tabular method (CIE, 1995) is used to generate the UGR value using standard conditions, allowing the production of simple tables for use in luminaire data sheets.

In addition to the original UGR, the CIE introduced a specific UGR index for small sources. It should be used when light sources have an angular subtense smaller than 0.0003 sr (CIE, 2002). The UGR equation for small sources is a function of the luminous intensity of the light sources, and not of their luminance.

In North America, another system for the empirical prediction of discomfort glare was defined by the Illuminating Engineering Society (IES). It is based on an index called the Visual Comfort Probability (VCP). This index evaluates the percentage of people who would judge the lighting system in its environment as not being uncomfortable using the perception of glare (DiLaura *et al.*, 2011). Like the UGR metric, the VCP system of evaluation is also based on a formula implying luminance, solid angle, position in the field of view, and luminance of the background. The correlation between UGR and VCP is high (Boyce, 2014), and the VCP system is rarely used at this time.

Overhead glare is a special case of discomfort glare with light sources located outside the field of view, at vertical angles typically greater than 53°. Such luminaires are not included in the calculations of common discomfort glare indices such as VCP and UGR. However, they may emit light on elements surrounding the eyes such as the eyebrows, the nose, the cheeks and any glasses that are worn (Boyce, 2014). According to Boyce, the luminance above which overhead glare occurs in indoor lighting is about 16 500 cd/m².

The common discomfort glare metrics were developed for indoor lighting. However, the CIE has reviewed several existing models of discomfort glare applicable outdoors to vehicle lighting and road lighting (CIE, 2021). There is currently no unified model for discomfort glare evaluation in these situations.

Unlike the case of disability glare, the age factor has not been considered in establishing the usual discomfort glare indices.

3.4. Specificities of LEDs and SSL with respect to glare

The previous IEA 4E SSL Annex report on potential health issues pointed out that LED components used in lighting often have a very high luminance (Zissis & Martinsons, 2014) even when their luminous flux is low. This is a consequence of their small emission area, typically of a few mm² for most individual LEDs.

Glare being associated with high luminance or high luminance contrast, SSL luminaires often incorporate optical systems such as mirrors, lenses, and diffusers. The resulting light intensity distribution is tailored according to the intended application. The luminance can be limited in the different viewing directions. However, SSL luminaires without any optical system are widely used in illumination applications where the user is not supposed to look directly at the source to avoid glare situations (floodlighting applications for instance).

Bare LEDs are sometimes used in non-directional SSL lamps (LED filaments for instance), but they should be used with a shade to limit discomfort glare. This is not the case of directional SSL lamps which are not intended to be viewed directly. Such lamps incorporate optical collimators to concentrate the light intensity distribution in a narrow beam, producing very high luminance values in the beam direction.

3.5. Analysis of the published research on glare since 2012

3.5.1. Disability glare

Disability glare has been well understood since the second half of the twentieth century. The invention of the LED and the worldwide diffusion of SSL products have not affected the comprehension and description of the basic phenomena. However, a more detailed analysis of disability glare was carried out to better understand the combined effects of retinal illuminance and light scattering by the eye at low light levels (mesopic range) (Patterson *et al.*, 2015). This study showed that the scattered light falling on the retina increased the retinal sensitivity in mesopic conditions, counter-intuitively leading to better visual performance than predicted without scattered light.

A study published in 2014 (Davoudian *et al.*, 2014) investigated disability glare in simulated night driving conditions. Participants were asked to assess the location and feature of two targets in the presence of a source of disability glare simulating an LED street lighting luminaire at night. Two different LED spectral distributions (cold white and warm white) and two apparent sizes (small and large) were tested. A total of 42 observers performed target detection tasks. Luminance contrast thresholds were measured for each observer under different levels of glare. No statistically significant differences between the results from the cold and warm glare sources or between large and small glare sources were found. Results showed that, while veiling luminance had a significant effect on the performance of observers, its effect was lower than expected from contrast loss. The results showed that while increasing veiling luminance significantly increases threshold luminance contrast in observers under 50 years of age, it had no statistically significant effect on observers over 50 years of age. The performance of observers over the age of 50 was unaffected by increasing the glare level. This finding was consistent with those of Patterson *et al.* who also showed that in mesopic conditions, the effect of glare on threshold contrast is less than what would

be predicted by a consideration of the change in effective contrast alone (Patterson *et al.*, 2015).

3.5.2. Discomfort glare from uniform large area SSL products in indoor lighting

Mou *et al.* found that discomfort glare from OLEDs and edge-lit LED panels, two different technologies of large area light source used indoors, were comparable and well-predicted by existing metrics of indoor discomfort glare (Mou *et al.*, 2016; Mou *et al.*, 2017) such as the UGR.

3.5.3. Discomfort glare from non-uniform sources in indoor lighting

Many SSL products incorporate multiple individual LEDs or LEDs arranged in linear or rectangular arrays (Yang *et al.*, 2017). These light sources have a common feature that no previous lighting technology exhibited. The light source is a regular pattern of non-uniform luminance, consisting of spatially alternating bright (individual LEDs) and dark areas (zones between individual LEDs).

A literature review on discomfort glare from non-uniform sources was published by Geerdinck *et al.* (2016). The authors analysed 60 papers, most of them published between 2012 and 2016, and identified the most relevant parameters influencing glare from non-uniform sources. All the studies investigated by the authors, except (Cai and Chung, 2013), found that non-uniform sources produced more discomfort glare than uniform sources of the same average luminance. More precisely, discomfort glare was increased when the LEDs were smaller or when the number of LEDs per surface area decreased (Yang *et al.*, 2017). A higher contrast between the bright and dark zones was associated with more discomfort glare (Ma *et al.*, 2017). The effect of the spacing between the LEDs was more complex. In direct viewing conditions, discomfort glare was increased when the apparent angular spacing was near the visual acuity of the viewer. According to Wilkins (2016), this finding could be explained by the high spatial frequency components in the spectrum of these regular patterns, particularly near the peak spatial frequency of human vision at around 3 cycles per degree.

The impact of the non-uniformity was more pronounced in central vision. With an eccentricity of 30°, the discomfort glare ratings differed only slightly between uniform and non-uniform sources of the same average luminance (Geerdinck *et al.*, 2016).

In 2019, the CIE published a technical report devoted to the effect of the effect of non-uniform sources on discomfort glare (CIE, 2019). The authors relied on the previously described literature review to emphasize that the UGR index tended to underestimate the discomfort provoked by luminaires having a highly non-uniform luminance. Several UGR correction methods were evaluated by comparison to experimental data on discomfort from uniform and non-uniform light sources. The CIE technical report defined a non-uniformity correction factor to the UGR index involving a precise definition of the glare source area based on luminance images of the non-uniform source taken from two orthogonal viewing directions (Simonot *et al.*, 2021). The CIE non-uniform correction solves the discrepancies between UGR and perceived glare from non-uniform light sources. In 2023 the CIE published a Technical Note to facilitate the necessary image capture for this calculation (CIE, 2023).

3.5.4. Discomfort glare from urban and road lighting LED luminaires

Villa *et al.* (2017) investigated discomfort glare of pedestrians from urban LED luminaires. Their findings showed that most discomfort glare models elaborated before the advent of SSL tend to overestimate the experimentally assessed mean subjective discomfort from LED urban luminaires. More recent models proposed by Lin *et al.* (2014) and Bullough *et al.* (2011) performed better than the older models. However, in a study performed using a scaled laboratory setup under 72 lighting conditions, the authors found general similarities in discomfort glare between LED and traditional road lighting luminaires (Liu *et al.*, 2015).

3.5.5. Discomfort glare from small light sources in outdoor dark environment

A study has found that the definition of the small source UGR, initially applicable to indoor environments, could be extended to predict the discomfort glare from small sources in outdoor nighttime environments (Tyukhova and Waters, 2018).

3.5.6. Discomfort glare from multiple light sources in the visual field

Girard *et al.* (2021) investigated discomfort glare from several white LEDs in the visual field in nighttime outdoor conditions. They established a formula which predicts the contribution to discomfort glare of more than one source in the visual field. The formula includes a summation of the luminance values (with a non-integer exponent) of the light sources, their positions in the field of view, and their apparent sizes. The formula cannot predict the absolute magnitude of discomfort glare produced by multiple sources. However, it is a first step toward a multi-source discomfort glare model that could be used to assess glare from outdoor lighting in real settings.

3.5.7. Influence of colour and spectral power distribution on discomfort glare

A study published in 2013 on discomfort glare from LED road lighting luminaires with similar intensity distributions concluded that a luminaire with a CCT of 3000 K was perceived less glary than a luminaire with a CCT of 6000 K by old and young participants (Zhu *et al.*, 2013).

An experiment was designed in dark ambient conditions to assess discomfort glare from LEDs emitting different colours of light, in comparison with an LED emitting white light (Yang *et al.*, 2018b). The results showed that coloured LEDs induced more discomfort glare than the white LED. When comparing different coloured LEDs, blue LEDs gave the highest discomfort glare perception, especially for those having a shorter peak wavelength.

Using dark ambient conditions, Bullough (2009) showed that the spectral sensitivity to discomfort glare can be modelled by the combination of the photopic luminous efficacy function and the spectral sensitivity of the short-wavelength cones. This study found an increased contribution of short wavelengths in discomfort glare as the peripheral angle of the glaring light source increased.

Some researchers have tried to model the spectral dependence of discomfort glare by introducing a spectral term in the UGR formula (Huang *et al.*, 2018) in order to extend its definition. These models were able to predict the observed increase of discomfort glare with CCT. The colour dependence of discomfort glare has also been successfully described using colour appearance models originally conceived to model colour vision in humans (Yang *et al.*, 2018a).

Skinner and Bullough (2019) investigated the influence of the spectral power distribution of light on the time needed for vision to recover after a brief exposure to a glaring source (automotive headlamp). Cool white LEDs were judged as creating more discomfort than warm white LEDs. However, the glare recovery times were identical for cool white and warm white LEDs under the range of conditions used in this study.

3.5.8. Neural mechanisms involved in discomfort glare

The poor understanding of neural mechanisms contributing to discomfort glare had led researchers to carry out new research in this area. Methods used in neurosciences have been used, such as functional magnetic resonance imaging (fMRI) and brain oximetry based on near-infrared spectroscopy (NIRS).

Both techniques demonstrated that brain oxygenation is greater when the visual stimulus is uncomfortable, reflecting an increased mental load (Wilkins, 2016). Wilkins argued that the degree of visual discomfort can be linked to the spatial frequency spectrum of the image viewed. Natural landscapes exhibit a spectrum in 1/f, where f is the spatial frequency. Artificial panoramas often depart from this behaviour, when peaks at specific spatial frequencies are created by regular patterns such as luminaire alignments, staircases, etc. Wilkins extended this research hypothesis by stating that temporal, spatial and chromatic characteristics differing from those of the natural world may cause inefficient neural processing, creating visual discomfort (Boyce and Wilkins, 2018).

Exploring this hypothesis, Penacchio *et al.* (2023) investigated markers of visual discomfort derived from the image content. In this study, participants assessed their visual discomfort on a semantic scale when looking at different images (architecture and art images) showed on a computer display. The images viewed by the participants were processed using a computational neurodynamic model of the early visual cortex. After regressing rated discomfort against different metrics of the model, calculated in different ranges of spatial frequencies, three markers of aversive images were identified: a high overall activation of the early visual cortex corresponding the total amount of activity of the neurons, a low sparse response (too many neurons have a high activity meaning that the image encoding is not efficient), and a more unbalanced distribution of neural activity across spatial orientations (reduced image isotropy). With architecture images, the visual discomfort of participant was best predicted by the three metrics applied to spatial frequencies between 1.5 and 6 cycles per degree, a range corresponding to the highest contrast sensitivity function of vision. The authors argued that three identified mechanisms may also explain interindividual differences in susceptibility to visual discomfort.

3.5.9. Influence of glare on migraine and photophobia

Glare has often been suspected to trigger headaches in people suffering from migraines. During a migraine episode, migraineurs usually avoid light as it may intensify their headaches. The aversion to light, or photophobia, also occurs in a range of other ophthalmic, neurological, and behavioural conditions (Wilkins, 2021). People suffering from a traumatic brain injury may also experience pain in response to glare (Albilali and Dilli, 2018). The visual discomfort associated with migraine can occur not only in response to bright light but also flicker, spatial pattern and colour (Wilkins *et al.*, 2021).

Using psychophysical assessments in patients with normal eyesight, Noseda *et al.* found that green light exacerbated migraine headache significantly less than white, blue, amber, or red lights (Noseda *et al.*, 2016). Using electroretinography and recordings of brain signals, the authors suggest that patients' experience could originate in cone-driven retinal pathways, relayed by neurons outside the main visual pathway and preserved by the cortex.

Green light emitted by LEDs was investigated as a potential therapy in patients with episodic or chronic migraines (Martin *et al.*, 2021). They found that controlled exposures to green LED light significantly reduced the number of headache days in people suffering from episodic migraines or chronic migraines.

Studying migraineurs and control subjects, Noseda *et al.* (2017) suggested that the aversive nature of light is more complex than its association with headache intensification. They found that light triggered more changes in autonomic functions and negative emotions during migraines episodes. The association between light and positive emotions was stronger in control subjects than in migraineurs. Studying rats, the authors also showed that axons of retinal ganglion cells converged on hypothalamic neurons that project directly to nuclei in the brainstem and spinal cord, potentially affecting many parasympathetic and sympathetic functions.

A novel light-sensing circuit, independent of the optic nerve, has been identified by Matynia *et al.* (2016) in the trigeminal nerve (the cranial nerve responsible for sensation in the face and for motor functions such as biting and chewing) and may influence behaviour under strong light. In mice, as in humans, about 3% of the neurons in the trigeminal ganglia with nociceptors (pain receptors) also contain melanopsin. These neurons are inherently sensitive to light. When isolated, they responded to an intense light of 480 nm. In mice, the light-aversion reflex was maintained after degeneration of optic nerve fibres. Only intense light triggered the response of neurons in the trigeminal ganglia.

Martenson *et al.* (016) investigated the aversion to light in patients with fibromyalgia, a pain disorder sometimes attributed to a dysregulation of the brain pain-modulating systems. These individuals expressed discomfort at light levels substantially lower than healthy controls. Complementary studies in lightly anesthetized rat demonstrated that a subset of identified pain-modulating neurons unexpectedly responded to light. These data demonstrated that light intensity signals were present at the level of single pain-modulating neurons in the brainstem of the rat under basal conditions.

3.5.10. Glare, asthenopia and muscular pain

Discomfort glare and disability glare both potentially disrupt binocular vision, resulting in measurable disparities in eye fixations. Disruption of binocular vision is strongly associated with asthenopia (eye fatigue) and is therefore believed to contribute to related symptoms reported during or after computer work.

A study investigated the effect of discomfort glare in direct (luminaire in the field of view) and indirect (luminaire reflection on a screen) configurations on binocular vision (Glimne *et al.*, 2013). Horizontal fixation disparity was measured while participants were performing tasks on a display unit in a typical office setting. Glare was found to have a significant effect on the variation of the measured fixation disparity values. Direct glare seemed to increase the

demand on the oculomotor system, attributed by the authors to increased efforts to maintain a precise adjustment.

Visual fatigue and task performance under LED and fluorescent lighting conditions were evaluated and compared by Wang *et al.* (2015) with participants completing a work-related task on a computer. The experimental results indicated that illuminance, CCT and the type of light source have effects on some symptoms of visual fatigue. Particularly, LED lighting was found to cause less visual fatigue than fluorescent lighting. However, the confounding effect of temporal light modulation, often present in fluorescent tubes, was not checked by the authors of this study.

A study by Mork at al. (2020) investigated the effect of several types of environmental stress during computer work, including direct glare from a large light source. The participants were a group of 43 healthy young females with normal binocular vision. The investigated outcomes were eyestrain, neck, and shoulder discomfort, altered moods, and reduced well-being. Exposure to direct glare induced greater development of visual/eye symptoms and discomfort. The perception of work lighting during glare exposure was closely related to perceived stress, and associations between visual discomfort and eyestrain, and neck pain were observed in all conditions. Furthermore, participants with high trapezius muscle blood flow overall reported more neck pain, independently of the exposure.

3.5.11. Physiological and behavioural responses to glare

In a review paper published in 2021 about the methods of evaluation of discomfort glare, Fotios and Kent (2021) emphasized the benefit of using involuntary physiological measurements and behavioural observations to avoid undesirable biases associated with subjective evaluations of discomfort glare. Physiological responses may provide a more objective evaluation and comprehension of discomfort glare (Lin *et al.*, 2015).

Hamedani *et al.* (2019) reviewed the existing literature on methods to measure light-induced physiological responses to objectify perceived glare. Physiological responses investigated within the reviewed literature included pupil size, eye movement, gaze direction, degree of eye-opening, and blink rate.

Using eye-tracking techniques, Glimne *et al.* (2015) showed that glare has a negative effect on reading performances. The more adverse the lighting condition was, the slower the reading speed became. The decrease was primarily a result of increased fixation durations.

Lin *et al.* (2015) carried out subjective evaluation of glare discomfort (category rating using the De Boer scale) while measuring eye movements and pupil constriction. Severe glare discomfort increased the speed of eye movement and caused larger pupil constriction (smaller pupil diameter). Larger variations of eye movement were found among senior subjects. The two physiological responses had significant correlations with the subjective evaluation. The authors hypothesized that their findings may offer an explanation as to why long-term exposure to discomfort glare leads to visual fatigue and eyestrain.

In a laboratory study, Lee *et al.* (2017) evaluated the effect of different glare sources (halogen, HID and LED) in car driving situations at night. Pupil diameter and electroencephalographic signals were measured. The discomfort glare was assessed subjectively using category rating.

It was found that the pupil size was significantly affected by the headlamp type and illumination condition. Pupil size was smaller when exposed to the LED headlamp than other headlamps. The driver's discomfort increased when pupil size was small and theta brain waves were high, which, according to the author, could be a cause of reduced attention and safety of the driver. It is not clear whether the results of this study could be applied the general lighting products studied in this report, as car headlamps have different technical characteristics.

In an experimental study carried out by Hamedani *et al.* (2020), the effects of lighting conditions on user physiological responses and visual performance were investigated using physiological measurements. The authors found that fixational eye movements were significantly increased in high discomfort conditions. Blink rate and amplitude were significantly affected by a high level of discomfort glare.

In a companion study (Hamedani, Solgi, Hine, and Skates, 2020), Hamedani *et al.* examined human subjects and their physiological, ocular and performance responses under different lighting conditions. The experiment was carried out in an office with daylight as primary light source. Physiological and ocular data were recorded by eye-tracking glasses. Data analysis suggested that several eye-tracking parameters (pupillary unrest index, blink amplitude, eye-fixation rate, and mean pupil diameter) could be used as a visual discomfort proxy. Pupillary unrest index and blink amplitude could be predicted better with relative glare factors (linked to contrast), while fixation rate and pupil diameter could be predicted better with absolute glare factors (luminance and illuminance). Concerning performance measures, this study identified that the combined visual performance index was negatively correlated with vertical illuminance at eye level and the average luminance. This index was also better when the pupillary unrest index was lower.

3.5.12. Age factor in discomfort glare

Age has not yet been considered in the published models and established indices predicting discomfort glare. However, the role of age in discomfort glare has been investigated in several studies.

A study by Kimura-Minoda *et al.* (2012) compared discomfort glare between a group of young observers and a group of elderly observers using a controlled laboratory experiment and a randomized protocol with repeated measures. Small luminous stimuli were presented in front of a dark background at the centre of the visual field. A subjective scale of category rating was used by participants to assess glare.

Young people were found to be more sensitive than the elderly to discomfort glare from blue, green, and amber coloured LEDs. For red and white LEDs, no difference by age was observed. A comparison of light sources confirmed that, for both age groups, blue LEDs cause discomfort glare at lower luminance levels than for other light sources. The cause of age differences in the perception of discomfort glare could not be solely explained by age-related changes in transmittance of the crystalline lens of the eye and in sensitivity to brightness.

Wolska and Sawicki, (2014) investigated discomfort glare in subjects aged 50 years and more in comparison with subjects younger than 35 years of age) The experiments were performed on a computer workstation placed in an unexceptional office room with two different

controlled discomfort glare conditions (UGR = 19 and UGR = 22) from linear fluorescent luminaires on the ceiling above and behind the computer display. Each participant performed visual tasks presented on the computer screen.

The glare evaluation method included subjective evaluation of discomfort glare on a semantic glare rating scale. The authors found that a higher percentage of the younger group subjects assessed glare as uncomfortable and intolerable than in the 50 years or older group, who more often assessed glare as acceptable. Younger participants more frequently reported asthenopic symptoms (eye fatigue). On average, the young group assessed lighting as being less comfortable, in comparison with the older group. The young group also rated discomfort glare more severely than the rating corresponding to the UGR value.

Tests of mesopic (low light) contrast sensitivity were carried out before and after the experimental session (in both glare conditions) in dark adapted conditions. Before the experimental session, the mesopic contrast sensitivity was found to be lower among the older group, a result that is consistent with the known decrease of low-light visual acuity with age.

After the experimental session, significant changes of mesopic contrast sensitivity were found only in the 50 years or older group, in both glare conditions. The authors indicated that this decrease in visual performance could be evidence of increased visual fatigue with the older group after a prolonged exposure to discomfort glare (the duration of the experimental session was about 65 minutes).

3.5.13. Influence of the time of the day on discomfort glare

The influence of timing of exposure on discomfort glare was studied by one research group. In a controlled laboratory experiment (Kent *et al.*, 2015), Kent *et al.* exposed subjects to an electric light source at four times of the day. Subjects were required to give glare sensation votes corresponding to the level of visual discomfort experienced. Glare indices were calculated for every reported glare sensation vote. The findings revealed a significant influence of the time of day on the subjective evaluation of the discomfort glare sensation. They indicated a tendency towards greater tolerance to luminance increases in electric lighting as the day progresses.

The experimental data obtained in the previous study were analysed in a follow-up study published by the same team (Kent *et al.*, 2016). They investigated the influence of self-reported personal factors including chronotype, an attribute reflecting individual circadian phases and assessed using an established chronotype questionnaire. They also studied caffeine ingestion before or between test sessions, as well as prior light exposure and sky conditions outdoors reported by participants before the experiments.

The results of this study showed that earlier chronotype test subjects (people feeling awake earlier) were able to tolerate higher levels of source luminance for the same reported criteria of visual discomfort at all times of the day.

The authors found a higher tolerance to source luminance across all criteria of glare sensation throughout the day for subjects not having ingested caffeine. This might be explained by the direct effect of caffeine on pupil dilation (Abokyi *et al.*, 2017).

The results did not bring any conclusive and consistent evidence of the influence of fatigue, sky conditions and prior light exposure on individual glare sensation at different levels of visual discomfort and times of the day.

In a further study Altomonte *et al.* (2016) explored potential relationships between visual task difficulty, temporal variables, and glare response as the day progresses. Under controlled laboratory conditions, they exposed 20 subjects to a constant electric source luminance at four times of day and gave glare sensation votes while completing twelve visual tasks of various difficulties. Self-assessments of temporal variables (fatigue, food intake, caffeine ingestion, mood, previous daylight exposure and sky condition) were provided by test subjects together with their glare judgements.

The results of this study confirmed the previous observations of the authors concerning the increased tolerance to electric source luminance along the day (Altomonte *et al.,* 2016). The temporal variation of glare response was found to be influenced by the difficulty in extracting information from the visual stimulus. The authors also found significant evidence of a direct effect of self-assessed fatigue and caffeine ingestion on glare sensation (higher fatigue and caffeine ingestion were each associated with higher glare sensations), and an inverse influence of food intake (food intake was associated with lower glare sensations).

3.6. Conclusions

3.6.1. Conclusions on disability glare

Disability glare is well understood. This type of glare is likely to be independent of the lighting technology. The basic mechanisms of disability glare are not altered by the type of lighting technology. SSL products, even with their specific spectral and spatial distributions of light, have not changed the occurrence of disability glare that has been experienced with high power luminaires used outdoors at night.

Two studies have been identified by our literature search in this area. The two studies confirmed the influence of age in this physiological phenomenon. While disability glare is associated with a decrease in visual performance, the studies revealed a more complex influence of scattered light associated with disability glare. In some situations, light scattered by the eye may improve the contrast sensitivity in mesopic (low light) conditions.

The decrease in contrast sensitivity associated with disability glare worsens with age, but one study showed that the decrease may slow after 50 years of age.

3.6.2. Conclusion on discomfort glare from SSL products

3.6.2.1. Discomfort glare in indoor lighting

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.

3.6.2.2. Discomfort glare in outdoor lighting at night

In street and road lighting, SSL luminaires do not seem to produce more discomfort glare than luminaires of older technologies. The studies investigated discomfort glare from distance which makes the glaring light source appear very small (point source). No study was found on the effect of the non-uniformity of street and road lighting luminaires. This non-uniformity becomes visible at closer distances.

Discomfort glare experienced outdoors at night from small light sources has not been extensively studied. The use of the small source UGR index in outdoor situations has not been yet validated.

Discomfort glare experienced outdoors at night from multiple light sources has not been extensively studied. The included articles provided some useful insights about the possible additivity of the contributions of individual light sources to discomfort glare.

3.6.3. Conclusions on the influence of colour and spectral power distribution on discomfort glare

Whereas colour and spectral power distribution do not seem to affect disability glare, it appears that these factors have an influence 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 power distribution in discomfort glare cannot be fully explained by the observed correlation between discomfort glare and CCT, as there are infinitely many possible spectral power distributions for any given CCT value. Furthermore, the role of colour rendering in discomfort glare has not been explored in the reviewed studies. Colour rendering is a complex property of light measured by several indices for colour fidelity and colour gamut. It is determined by the complete spectral distribution of light.

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.

3.6.4. Conclusions on migraines, photophobia, asthenopia, and neural outcomes with discomfort glare

Empirical evidence of a link between visual discomfort and neural responses such as the haemodynamic response (blood flow to neuronal tissues) of the brain has recently emerged. The use of the latest available tools used in neuroscience is a promising approach to investigate the biological correlates of visual discomfort and provide a deeper understanding of its multiple root causes. The Wilkins hypothesis for visual discomfort based on the spatial frequency content of viewed images (repeating patterns with specific periodicities) was partially explained using a computational model of the early visual cortex.

Glare can trigger and aggravate headaches in people suffering from migraines. This is the case of SSL products having high luminance or producing high luminance contrasts with their environment. It is not clear whether other sensitive population might exist.

The mechanisms linking strong light levels and headaches have been investigated by several teams. The contribution of visual pathways has been demonstrated, with a possible influence of the spectral distribution of light. Two independent research teams concluded the green light is the least active in triggering headaches among the other tested colours. A research team also found that repeated exposures to green light had a positive effect on migraineurs. This finding has not been replicated in the articles analysed in this review.

A non-visual pathway implying the trigeminal nerve has been identified by a research team seeking to better understand light aversion. A small percentage of neurons in this nerve, containing both pain receptors and melanopsin, could be triggered by strong light. Another research team identified an intrinsic sensitivity to light in pain-modulating neurons in the rat.

Taken together, these results may explain the existence of a novel mechanism of photosensitivity involving pain receptors and pain modulators responsible for aversive or painful responses to glare in sensitive people.

Discomfort glare experienced when performing work-related visual tasks during a long time is a factor contributing to asthenopic symptoms (eye fatigue) during or after completing the visual tasks.

When discomfort glare is present, no potential effect of the lighting technology has been identified in the occurrence of asthenopic symptoms.

The only study investigating the link between glare and muscular pains during computer work found a positive association between direct glare and neck pain. More research is needed to establish a link between discomfort glare and muscular pains.

3.6.5. Conclusions on the physiological and behavioural responses to glare

Physiological measurements are increasingly being used in lighting research to measure involuntary responses to visual discomfort, including discomfort glare. Eye-tracking, or oculometry, has been the main experimental technique used in the study of the physiological effects glare. Other types of measurements such as electroencephalography were sometimes performed in the reviewed studies.

Eye-tracking revealed the altered behaviour of the eyes during an exposure to a glaring source, an alteration not consciously perceived by the subjects during the tasks. Several eye-tracking parameters can be used as indicators of discomfort while a specific visual task is performed.

Although the studies were conclusive and established correlations between eye-tracking parameters and visual discomfort, no research has yet attempted to build a discomfort glare model from physiological responses. More research is needed to standardize physiological measurements and identify the most relevant parameters, or set of parameters, able to detect discomfort glare during the completion of different visual tasks.

3.6.6. Conclusions on the effects of age on discomfort glare

Discomfort glare sensation has been shown to change with age. Younger people were consistently found to be more sensitive to discomfort glare, after very short exposure times.

In one reviewed study, young people were also more sensitive to asthenopia induced by a source of discomfort glare.

Despite being less sensitive to discomfort glare than young people, older subjects experienced a decrease in their visual performance in low-light conditions after a prolonged exposure to discomfort glare.

3.6.7. Conclusions on the influence of time of the day on discomfort glare

The results of several studies performed by the same research group demonstrated that the subjective sensitivity to discomfort glare was high in the morning and tended to decrease along the day, even after correcting for several confounding factors.

The influence of the chronotype of the subjects was studied. The results showed that subjects of earlier chronotype were more tolerant to discomfort glare at all times of the day.

The mechanisms explaining this circadian change of sensitivity to discomfort glare are not known.

3.7. Recommendations

3.7.1. Recommendation on disability glare

More research is needed to better understand disability glare and its consequence on visual performance in children and other sensitive populations, such as people having eye diseases.

3.7.2. Recommendation on glare from SSL products

Large-area, uniform SSL products can be recommended to limit discomfort glare in indoor lighting. Manufacturers of non-uniform SSL products should promote the use of the corrected UGR defined by the CIE to assess discomfort glare from their products. If the corrected UGR is not available, non-uniform SSL products should not be used in premises where long-term exposures can be foreseen, such as schools and offices.

More research is needed to evaluate discomfort glare from SSL street and road lighting luminaires in situations of proximity between the subject and the luminaire. At close distance, the effect of the non-uniformity cannot be neglected, and it should be studied in a similar fashion as previously done in the case of indoor lighting.

More research is needed to better understand discomfort glare from small sources outdoors at night, and to investigate and quantify discomfort glare from multiple outdoor light sources at night.

SSL products used at short viewing distance should be shaded or diffused to lower discomfort glare.

3.7.3. Recommendations on the influence of colour and spectral power distribution on discomfort glare

The influence of the spectral distribution of light on discomfort glare should be further researched to improve the existing discomfort glare indices.

Cool-white lights should be used with care in the presence of people sensitive to discomfort glare.

3.7.4. Recommendation on migraines, photophobia, asthenopia, and neural outcomes of discomfort glare

Lighting researchers and neuroscientists should carry out more multidisciplinary research to better understand the mechanisms linked with visual discomfort and explore the relationships between environmental stimuli and neural responses.

As some SSL products may produce high luminance levels or high luminance contrasts with their environments, they should be used with care in the presence of people suffering from migraines and people generally averse to strong lights. The direct viewing of high-power SSL luminaires is not recommended for these sensitive populations.

The lighting of workplaces should be designed using visual ergonomics principles to prevent discomfort glare and protect workers against work-related asthenopia and muscular pains.

3.7.5. Recommendations on the physiological and behavioural responses to glare

The use of eye-tracking techniques and other physiological measurements is encouraged in research on discomfort glare in addition to traditional assessment methods based on questionnaires, category rating, and objective scores from visual tasks.

The on-site use of physiological measurements to assess discomfort glare from a real lighting installation is not yet recommended given the complexity of the experimental techniques and the absence of physiological measurement standards devoted to visual tasks.

3.7.6. Recommendations on the effects of age on discomfort glare

Discomfort glare should be studied with younger populations such as children to better assess the quality of lighting systems in schools.

Since different outcomes were identified with discomfort glare for young and old subjects, this effect should be assessed at all ages of life.

3.7.7. Recommendations on the influence of time of the day on discomfort glare

More research is recommended to confirm the findings concerning the circadian variations of discomfort glare observed in the reviewed studies. It would be useful to investigate whether the observed circadian variation of discomfort glare could be driven by the excitation of the ipRGCs known to be involved in the regulation of the central biological clock and in the pupil constriction reflex.

Since discomfort glare may vary during the day, it might be useful to consider adapting light levels according to the time of day, notably in the morning when the sensitivity to glare is higher. However, there might be an apparent conflict between the need of a certain level of circadian light exposure and the higher sensitivity to discomfort glare that may be experienced in the morning. More research is needed to study a possible trade-off.

4. Temporal Light Modulation

4.1. What is temporal light modulation?

4.1.1. Background

The phrase temporal light modulation (TLM) is comparatively new, but the problem it describes is familiar. TLM refers to variations over time in the luminous or chromatic output of a light source (CIE, 2021). As will be shown below, TLM is the stimulus that triggers a broad range of neurological, perceptual, health and cognitive outcomes.

TLM arises from the responsiveness of the light source or lighting system to changes in the input power. In the case of resistance light sources (incandescent lamps), variations can occur in the mains power, but these are muted by the thermal inertia of the filament. Discharge lamps (fluorescent, HID, metal halide) require ballasts to control the current, which can introduce TLM; similarly, LED lamps and systems require electronic drivers to regulate the power that produces light.

TLM occurs with most electric light sources but has increased in complexity and importance with the development of LED devices. Legacy light sources of the same type (e.g., incandescent; magnetically-ballasted fluorescent lighting systems) tended to exhibit the same TLM behaviour regardless of the manufacturer. Incandescent lamps and magnetically ballasted fluorescent lighting systems exhibited TLM at twice the mains frequency (therefore 100 Hz in Europe, Asia, Africa and Oceania; 120 Hz in the Americas and Japan). Electronically-ballasted fluorescent lighting systems operated between 20,000 – 40,000 Hz. Such general statements cannot be made about LED devices because they vary widely in the electronic circuitry that drives the light output. Nearly every product will have a different TLM characteristic (Poplawski *et al.*, 2011). Four examples of TLM are shown in Figure 4.1. The upper left is an idealised waveform illustrating the regular sine wave that is characteristic of an incandescent lamp, in this case having a frequency of 120 Hz and modulation depth of ~6%. The upper right is the idealised rectangular wave of an LED system with PWM dimming at 500 Hz and 100% modulation depth, in this example with a 50% duty cycle. The lower left is the measured output of an LED replacement lamp with a frequency of 120 Hz and modulation depth of 14.1%. On the lower right is a measured output from an LED replacement lamp with 120 Hz frequency and ~86% modulation depth.

In addition to the inherent TLM of the technology, TLM can be deliberately introduced using controls. One reason to do this could be to provide a flashing light (pulsing at a low frequency) for signalling. Another reason would be to introduce dimming control to LED lamps and lighting systems using pulse-width modulation (PWM).

There have been few reported problems associated with TLM in incandescent lamps (an exception being occasional issues with dimmer compatibility), but magnetically ballasted fluorescent lamps were the target of complaints about eyestrain, headache, and malaise (Brundrett, 1974; Lindner and Kropf, 1993; Stone, 1992; Veitch and Gifford, 1996). Energy efficiency was the impetus for the development of electronic ballasts for fluorescent lighting systems, but researchers found that effects of the new ballasts on viewers were beneficial by comparison to magnetic ballasts (Veitch and McColl, 1995; Veitch and Newsham, 1998).

Regulations made electronic ballasts mandatory in many jurisdictions. Interest in this research topic waned until the advent of LEDs, with their infinite variations of system design and light output waveforms. LEDs have provided both a reason to study the effects of TLM on observers, and a highly controllable light source with which to do so.

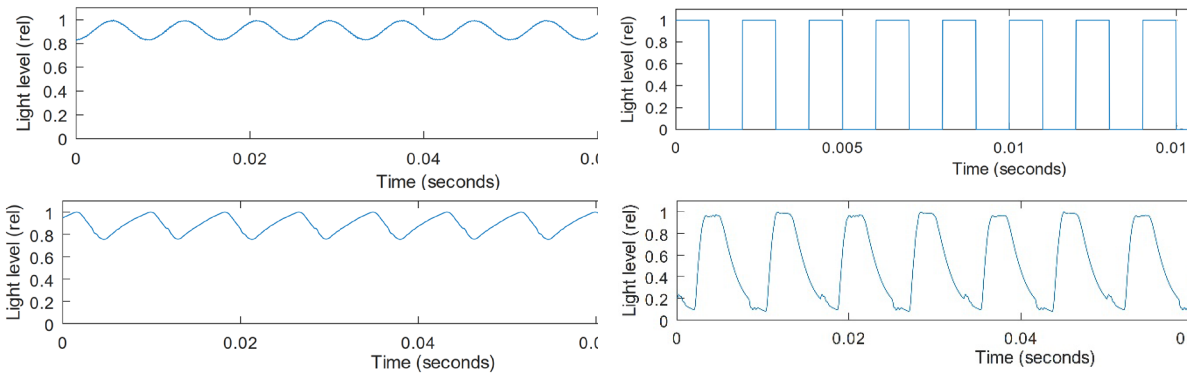

FIGURE 4-1. FOUR EXAMPLES OF TLM THAT ILLUSTRATE THE WAVEFORM VARIABILITY THAT CAN EXIST

As LED devices proliferated in the early 2000s and the diversity of TLM waveforms became apparent, committees began to be struck in standards development organizations and the research community responded to the need for more information with new investigations. The focus of many has been the development of new indices, derived from processing of LED waveforms to provide numbers that enable comparisons between different waveforms and to predict which waveforms will cause unwanted effects for viewers (Lehman *et al.*, 2011). Stakeholders agree that limit values of such indices could be the basis for regulations that will protect the public (CIE, 2017). Two examples of this application, both based on visual perception effects (discussed below), are seen in the European Union *eco-design* regulation for light sources (European Commission, 2021).

4.1.2. Measurement

Accurate measurement of the temporal variation in light output must be the starting point for both understanding and predicting its effects. At the present time, there is little consensus on how best to measure TLM waveforms to a high standard of metrological precision, as had been called for by stakeholders (CIE, 2017), although preliminary guidance on measurement exists (CIE, 2021) and a CIE technical report is in development by CIE TC 2-89. In the IEC, technical reports describe measurement methods for two quantities: IEC TR 61547-1 for P_{st}^{LM} and IEC TR 63158:2018 for the stroboscopic visibility measure, with projects in IEC/TC 34/WG 5 working on related standards (information as of May 2024). There is one national standard describing recommended measurement methods for TLM waveform capture (Illuminating Engineering Society (IES), 2020b), with somewhat different requirements from the CIE. Research is ongoing into establishing measurement uncertainties (e.g., Dekker and van Bloois, 2023; Mantela *et al.*, 2023).

TLM has four fundamental parameters: dominant frequency; modulation depth; waveform shape; and, for rectangular waves, duty cycle. From these fundamental measurements, researchers seek to develop integrated indices that combine these characteristics in order to

predict behavioural and health outcomes (Lehman *et al.*, 2011). Some of these indices are discussed in the sections that follow in relation to the outcomes being predicted. Technical reports developed from this research are used in place of international standards for TLM measurement (IEC, 2020, 2018; National Electrical Manufacturers Association (NEMA) Lighting Systems Division, 2017), but as noted above they do not include consideration of measurement uncertainty. This remains a field in need of further research attention because the indices are difficult to calculate and can produce inconsistent results across variations in measurement methods and data processing techniques (Tan *et al.*, 2023).

Advances in precise measurement will be needed hand-in-hand with advances in understanding the effects on observers because of the critical importance of establishing comparability of conditions across investigations in order to support guidance on limit values. Where regulations are in place to limit TLM in light source and lighting systems, metrological precision is required for conformity assessment and enforcement. Further discussion of these issues is beyond the scope of this report.

4.2. Effects of TLM on observers

4.2.1. Population sensitivity

The existence of individual differences in sensitivity to TLM has been known for half a century. Brundrett (1974) explored sensitivity to 50 Hz and 100 Hz TLM from fluorescent lighting systems with the aim of identifying the characteristics of sensitive people. He considered the effects of age, headache incidence, and certain viewing conditions. He found that sensitivity peaked around age 20 and declined thereafter. Headache sufferers showed different electro-encephalography (EEG) responses to flashing lights than healthy controls. Field survey data reported in the same paper show that headache sufferers were more likely to report seeing flicker.

Bosten *et al.* (2017) found that what they called *flicker sensitivity* was negatively correlated with age. Flicker sensitivity correlated positively with average pupil size and macular pigment density. As far as we are aware, these findings have not been further explored in relation to TLM sensitivity.

Wilkins and Evans (Evans and Stevenson, 2008; Wilkins and Evans, 2012) developed a diagnostic test (the *Pattern Glare Test*) to identify people susceptible to spatial and temporal patterns, which are associated with susceptibility to headaches, eyestrain, and epilepsy (Wilkins *et al.*, 1990). It involves viewing three striped patterns differing in spatial frequency (0.5, 3, and 12 cycles per degree [cpd]) and reporting on any visual illusions experienced. In a sample of 100 UK citizens of varying ages, 5% had a clinically significant difference score between the 3 and 12 cpd patterns. Scores correlated with age, younger observers being more likely to score high (Evans and Stevenson, 2008). People scoring high on the Pattern Glare test are at risk for headache and visual disturbances while reading (Harle *et al.*, 2006). This test has been used as an identifier for sensitivity to TLM in a few studies described later in this review (Veitch and Martinsons, 2020; Veitch and Miller, 2024).

The Pattern Glare Test can be difficult to administer because it requires a precise viewing distance to achieve the intended visual size of the striped targets, particularly for the highest spatial frequency (Wilkins *et al.*, 2016). Requiring individual testing by a trained individual is

practical for diagnostic purposes but less so in a research environment. The Leiden Visual Sensitivity Scale (LVSS) is a 9-item questionnaire that provides a simple alternative (Perenboom *et al.*, 2018). It has been validated against the Pattern Glare Test and can distinguish between individuals who are susceptible to migraines, particularly those who experience auras. Participants with migraine scored higher on the LVSS and on the Pattern Glare test than control participants, and also reported a lower illuminance threshold for visual discomfort in response to variations in light level of an incandescent lamp (i.e., with low TLM). This questionnaire has been used in one study reported later (Miller, Rodriguez-Feo Bermudez, *et al.*, 2023).

What would be of interest, but is not yet known, are population norms for sensitivity to TLM, for example testing a large random sample of the population using the LVSS. Knowing the distribution of high scores would contribute to understanding the scale of potential problems, and in targeting remedial measures. Such an effort would contribute to improving equity such that the full range of the population can enjoy the illuminated environment (Royer, 2020).

4.2.2. Brain activity and neurology

Experimental data that brain structures respond to TLM is generally considered to start with Eysel and Burandt (1984), who showed with an electrode implant in the cat that the lateral geniculate nucleus responded in a phase-locked way to fluorescent lamps at both 50 Hz and 60 Hz operation (i.e., with TLM at either 100 Hz or 120 Hz). Berman and colleagues (1991) used electroretinogram measurements of observers looking at common workplace equipment (fluorescent lighting, video display terminals) to demonstrate neuronal responses to TLM up to 200 Hz. At the time, these were the highest frequencies of common workplace technologies, and this placed an upper limit on the conditions that they could test.

The “canaries in the coal mine” for TLM are photosensitive individuals who experience either migraine headaches or epilepsy. The photosensitivity can be to both temporal variations in light intensity or spectrum (TLM) and to spatial variations (i.e., striped patterns) (Wilkins *et al.*, 1990). Photosensitive migraine and epilepsy both indicate observationally that ocular exposure to TLM has triggered a neural response; experimental data show that seizures start in the visual cortex Wilkins *et al.* (1990). The prevalence of photosensitive epilepsy could be as high as 1 person in 4000, with younger people (ages 5-24) being more sensitive (Fisher *et al.*, 2022).

The recommended practice document IEEE 1789-2015 summarized the variables that influence photosensitive epilepsy:

- pulses in the range 3 Hz to 70 Hz (with the greatest risk between 15 Hz and 20 Hz);
- the luminance of the pulse;
- its contrast with the background;
- the retinal area exposed and its location (central stimuli being more of a risk); and
- wavelength, with red pulses being most problematic.

The associated risk assessment concluded that the evidence for the risk of epilepsy is backed by solid data and expert opinion (IEEE Power Electronics Society, 2015), and it reiterated guidance from the Epilepsy Foundation of America Working Group that TLM ought not to

exhibit variations of more than 20 cd/m^2 for pulses in the range 3 Hz to 65 Hz. A 2022 review from the Epilepsy Foundation narrowed this range to 3 Hz to 60 Hz (Fisher 2022).

Outside this sensitive subgroup for which exposure to TLM could prove catastrophic, other evidence illustrates the effects that TLM can have on brain function. Wilkins (1986) demonstrated that TLM from magnetically ballasted fluorescent lamps at 100 Hz and ~36% modulation depth disrupted saccadic movement, with larger saccades occurring under this lighting than when the fluorescent lamps were operated with an electronic ballast at 20 kHz and effectively no modulation. Wilkins (1986) also reported an experiment contrasting 50 Hz and 100 Hz video display terminal (VDT) operation in which there were statistically significant differences in the size and number of saccades between the two conditions. Kennedy and Murray (1991) explored this further by comparing VDTs operating at 50 Hz and 100 Hz, also finding that the higher-frequency refresh rate disrupted the saccades more, resulting in more saccades being required to process the text (although the exact nature of the disruption depended on the participants' experience of on-screen reading). A follow-up experiment with a larger range of conditions (50, 75, 100 and 125 Hz and both positive and negative display polarity) also supported the hypothesis that the variations in luminous conditions (TLM) directly disrupted saccadic control.

Wilkins (1991) argued that this disruption in eye movements increases the neural computations required for task performance. If this is true, one would expect to see that brain activity changes under conditions of greater TLM. A few studies have examined this question, both with legacy technologies and, more recently, with LEDs. Küller and Laike (1998) used EEG to measure brain activity during task performance under two fluorescent lighting conditions, a magnetic ballast (100 Hz) and an electronic ballast (~ 20 kHz). They did not observe TLM effects in the sample as a whole (N = 40). When they split the sample by the critical flicker fusion frequency (CFF), they observed an effect for the more sensitive group (with higher CFF): Activity in the alpha EEG band (8-12 Hz, a state of relaxed wavefulness; VandenBos, 2015) was lower (indicating greater physiological arousal) under the low-frequency TLM condition (i.e., 100 Hz with magnetic ballasts); they did not detect differences in the beta EEG band (13-30 Hz, associated with alertness and mental activity (VandenBos, 2015).

Experiments contrasting different LED lighting systems have also found that TLM affects brain activity. Combining these studies into a single framework is difficulty because the experimental conditions and the reported outcomes differ widely between studies. Niemierzycka (2018) compared a mixed variety of fluorescent and LED lighting products and reported levels of beta EEG band activity (typical of waking consciousness), studying a sample of 20 young adults. (If they examined alpha band activity, they did not report it.) The LED products exhibited TLM of 122 Hz with rectangular waves varying in duty cycle (and correlated colour temperature). This team found that beta activity varied for different conditions, with the highest activity seen for the PWM condition with shortest duty cycle (19%). The authors interpreted this finding as suggesting that this condition might be a desirable one for workplaces. However, they did not see effects one might expect in contrasts between magnetically ballasted and electronically ballasted fluorescent lamps, for which the variation in TLM was considerably larger.

Zhao, Hou, and Lin (2020) compared nine TLM conditions (100 Hz, 400 Hz, and 1500 Hz frequencies and 10%, 30%, and 70% modulation depths), and measured EEG activity during

exposures of approximately 25 min. Frequency, but not modulation depth, affected brain activity in the occipital lobe (there were no effects in the frontal lobe). Alpha activity was lower for the 100 Hz conditions (regardless of modulation depth) than the 1500 Hz condition, indicating greater arousal at the lower frequency and consistent with Küller and Laike (1998). Similarly, beta wave activity was greater for 400 Hz than 100 Hz and for 1500 Hz compared to 400 Hz.

Taking a different approach, Veitch *et al.* (2024) used EEG data, but instead of conducting a frequency analysis, they reported strength of brain activity using dipole source analysis, and also examined event-related potentials during visual tasks. There were three conditions: a no-TLM condition, a 100 Hz rectangular wave with 50% duty cycle and 100% modulation depth, and a 500 Hz rectangular wave with 50% duty cycle and 100% modulation depth. They observed that both 100 Hz and 500 Hz conditions appeared to increase physiological arousal (as indexed by pupil size) and the presence of TLM changed the timing of brain activity in response to a visual stimulus. The dipole source analysis located brain activity during tasks differing in difficulty and involving word and colour processing. There were interactions between task difficulty, hemisphere, and TLM. Overall, brain activity was observed to be higher for the 100 Hz condition than either no-TLM or 500 Hz, in the right hemisphere, and during the easier trials.

What does increased brain activity mean? Wilkins (1995) has hypothesized that complaints of discomfort from visual stimuli including uncomfortable patterns and TLM arise from increased cortical activity. There is evidence for this from studies comparing images that deviate from natural statistics for spatial frequency (Penacchio *et al.*, 2023), but few that have examined TLM. Patterson and Gentile (2020), however, compared brain activity and ratings of discomfort for TLM conditions ranging between 1.625 and 30 Hz (i.e., very low compared to LED light sources), for healthy individuals and people susceptible to migraines. There were no differences between the two groups, although the group sizes were small (N=10 each). There was, however, a clear linear relationship between cortical activity and ratings of discomfort, thus establishing a biological basis for visual discomfort in response to TLM.

4.2.3. Visual perception

Visual perception effects occur nearly instantaneously with TLM exposure and are comparatively easy to measure, usually by asking a single question about what the observer sees. More than a century of research in this area has led to grouping the visual perception effects in three categories: flicker, stroboscopic effect, and phantom array effect (CIE, 2016).

Collectively these are sometimes called *temporal light artefacts* (CIE, 2016). This term can be problematic because it has been used in a manner that conflates the stimulus (TLM) with the response (visual perception) (Miller and Veitch, 2021). For example, NEMA (2017) titled its measurement document “Standard for temporal light artifacts: Test methods and guidance for acceptance criteria”. This implies that when one measures the light output in the temporal domain from a lighting system or light source, one measures the perception (the artefact), but this is only the stimulus and not the response.

4.2.3.1. Flicker

Flicker is a familiar phenomenon: One looks at a light source and immediately detects variation in its output. This word is also often used to refer to TLM of any kind because of its

colloquial definition. However, this use is also problematic because TLM conditions that do not result in a visual perception effect also influence observers, as shall be seen.

Flicker has an official definition in the International Lighting Vocabulary: "perception of visual unsteadiness induced by a light stimulus the luminance or spectral distribution of which fluctuates with time, for a static observer in a static environment" (CIE, 2020). Note that the temporal variation can be either in the amount light or its colour (Bimler, 2010), although most of the research discussed here has focused on luminance variations.

As noted above, flicker is a useful perception in certain applications, where the intent is to make a signal obvious because it varies over time. Thus, we see flashing signal lights to mark hazards on a road, or to indicate when an electronic device is operating. Some writers (e.g., Bodington *et al.*, 2016) would categorise the perception caused by light sources varying between 0-5 Hz as *flash*, a separate phenomenon. There is a robust literature on brightness perception and conspicuity of flashes that guides application designers and standards development organizations wanting to use flashes to provide information to observers; this is not a general lighting application and is therefore outside the scope of this report. (Although arguably this use of TLM could be said to have a beneficial effect on health if it warns of a dangerous situation and leads to the avoidance of a hazard.) TLM of a small source at relatively high frequency, can be perceived as twinkle (Nakajima and Sakaguchi, 2015), which can also be used for aesthetic effect, but is also outside the scope of this report.

Miller, Leon, Tan and Irvin (2023) recently reviewed the literature concerning flicker, and the other visual perceptions that TLM causes. Miller *et al.* noted that flicker detection varies as a function of frequency, modulation depth, waveform shape, luminance, and adaptation luminance. There is general consensus that the eye-brain frequency response function for a sinusoidal wave peaks between 7-15 Hz, but flicker may be detected at quite low modulation depths if the retinal illuminance is high, and its visibility is higher for a rectangular wave than a sinusoidal wave. The frequency threshold for an individual above which they no longer perceive individual pulses is known as the *critical flicker fusion frequency*. CFF values for an individual typically range between 50 – 90 Hz depending on the luminance of the source and whether or not the individual is fatigued. Contextual factors also influence flicker visibility, notably the size of the light source and its position in the visual field.

There are those who have argued that it ought to be possible to use TLM responses to good effect. For example, Rieiro *et al.* (2012) suggested that by using known effects of flashing lights on brightness perception, it ought to be possible to tune LED operation to human visual perception in order to reduce energy use. They proposed that operating LEDs at 13 Hz and 100% modulation depth in a with an 87% duty cycle would enable energy savings. Few in the lighting industry would recommend subjecting observers to continuous, obvious flicker. Indeed, in the industry it is the norm to seek to exclude the possibility that lighting systems will result in flicker.

Three indices have been proposed to predict flicker from measured TLM waveforms, one of which is most commonly used. The most-used index is the IEC Flickermeter, or P_{st}^{LM}. (IEC, 2020). This index is used in the European Union *ecodesign* regulation (European Commission, 2021). It has been defined in a technical report and not an international standard, which lacks some of the measurement precision that would be desirable (Tan *et al.*, 2023). This index is

an adaptation of a classical method for measuring perturbation of electrical supplies, for which a voltage variation was the measurement. For the purpose of predicting flicker, a light measurement is used instead, hence the LM superscript. Calculation of this index requires several minutes of data collection. P_{st}^{LM}. calculations are carried out in the time-domain, making this index applicable to periodic, aperiodic and transient TLM waveforms. Although described as a method addressing flicker from 0-80 Hz, the calculation method has a low-pass filter that excludes components greater than 35 Hz. Furthermore, there do not appear to be any contemporary investigations that have explicitly tested this index for its predictive value of flicker perception using a variety of light sources and waveforms.

A body of research from the Lighting Research Center in Troy, NY, which began in the early days of the LED revolution, led to the development of a metric known as *Mp* (Bodington *et al.*, 2016). This metric is based on first principles and original empirical data. It includes TLM frequencies from 5-90 Hz. Miller *et al.* (2023) noted that *Mp* and P_{st}^{LM} correlate well, but *Mp* is calculated in the frequency domain and may be calculated from a shorter data collection period.

The third index, also not frequently used, is the Flicker Visibility Measure (FVM) (Perz, Sekulovski, Vogels, *et al.*, 2017). It was derived from empirical data and grounded in the visual perception literature. It is also based on a frequency-domain calculation. FVM is a weighted sum of the relative energy of the frequency components of a measured TLM waveform up to 80 Hz. The developers demonstrated its superior predictive quality in comparison to other indices, particularly modulation depth and the Illuminating Engineering Society (IES) Flicker Index (Illuminating Engineering Society (IES), 2020a); it performed approximately as well as P_{st}^{LM} and had the potential to be extended to predict aperiodic TLM as well. The fact that the paper was published around the same time as the technical report defining P_{st}^{LM} (IEC, 2020), which was familiar to the industry in its early form for electrical supply, possibly accounts for the apparent lack of follow-up investigations using the FVM.

4.2.3.2. Stroboscopic motion

The stroboscopic effect lacks a standard definition, but has been defined in a CIE technical report as: “change in motion perception induced by a light stimulus the luminance or spectral distribution of which fluctuates with time, for a static observer in a non-static environment“ (CIE, 2022). The problem it describes is that of a moving object appearing to be still or moving in a jerky fashion. It has been known for decades and used for effect in film and theatre, and as a risk to be avoided in industrial settings. Figure 4-2 illustrates this effect using a replication of a moving task developed by Vogels, Sekulovski and Perz (2011). When there is little TLM, as in the centre panel, the rotating white dot appears as a moving smudge, but with a larger degree of TLM one sees a sequence of individual dots.

Figure 4-2 presents a white dot on a black disk which has been used in several experiments into the effects of TLM on the stroboscopic effect. The left image shows the disc when it is not rotating. The centre image shows the disk moving at 4 metres per second (m/s) and photographed when lit by the lamp with a TLM waveform shown in the lower left image of Figure 4-1. The right image in Figure 4-2 shows the rotating disk at the same speed when lit by the TLM waveform shown in the lower right image of Figure 4-1.

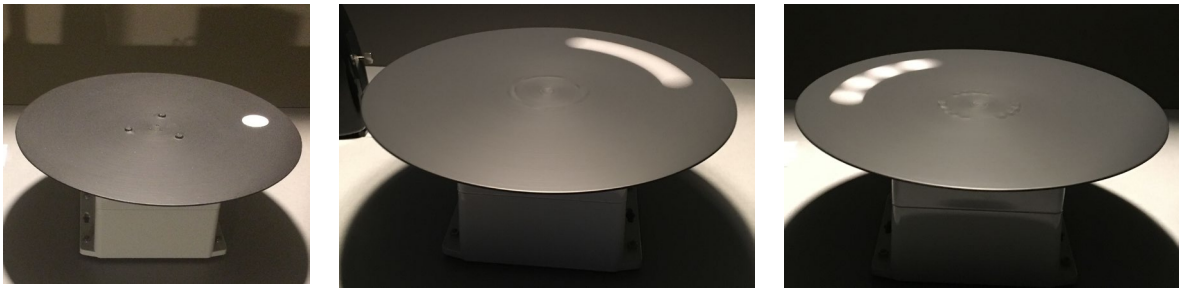

FIGURE 4-2. A WHITE DOT ON A BLACK ROTATING DISK ILLUSTRATING THE EFFECTS OF TLM WAVEFORMS

Two laboratories conducted extensive investigations into the visibility of the stroboscopic effect as it might be experienced in offices lit with LED lighting, both starting around 2011. In the United States, Bullough and colleagues examined a broad range of conditions in various experiments (Bullough and Marcus, 2016; Bullough *et al.*, 2012; Bullough *et al.*, 2011), from 50 Hz to 10 000 Hz frequency, various modulation depths, various waveform shapes and (for rectangular waves) duty cycles. In different experiments the visual tasks varied from the motion of a metronome arm (1.7 m/s motion), the visibility of a white wand waved by the observer over a black surface, and the visibility of the observer's own hand. The experiments found that stroboscopic visibility varied sigmoidally with the TLM frequency (depending on the experiment, with peak detection between approximately 100 and ~400 Hz) and with the modulation depth (higher detection with greater modulation depth), with varying visibility for different waveform shapes and higher visibility for lower duty cycles of rectangular waveforms. They developed acceptability contour plots based on frequency and modulation depth (Bullough *et al.*, 2012), and later concluded that for a given frequency the IES Flicker Index provided an adequate prediction of stroboscopic visibility for practical purposes; furthermore, they suggested that by modifying the flicker index using the multiplier 100/*f*, one could compare values across light sources with different TLM frequencies. They suggested that the measurement and computation of such an index would make it practically useful.

In parallel a team in Europe developed the Stroboscopic Visibility Measure (SVM, or M_{vs}) with data from a series of experiments in which the moving task was the rotating disc shown in Figure 4-2 (Perz *et al.*, 2018; Perz *et al.*, 2015; Vogels *et al.*, 2011). The SVM is a specific derivation of a general equation from vision science and predicts the visibility of the stroboscopic effect as the sum of frequency components in the TLM signal between 0 and 2000 Hz, weighted by a temporal contrast sensitivity function. It is normalized such that a value of 1 represents the threshold (50% detection) response of an average viewer. That is, the developers intend that the stroboscopic effect ought to have a lower-than-chance probability of detection for a light source with SVM < 1 when viewed by the average observer. The SVM is intended for applications in general interior lighting with average horizontal illuminances of 100 lx or greater. The rotating disc task was designed to replicate the typical motion of the hand made by a subject in an office environment (speed of 4 m/s). Therefore, the task does not produce stroboscopic effects associated with tools, machine, or objects moving at higher speed, nor does the SVM apply to moving objects at higher speeds.

The original contrast sensitivity function (Perz *et al.*, 2015) was derived from experiments including, at varying frequencies from 50 to 800 Hz, rectangular waves of varying modulation

depths at 50% duty cycle, and sine waves of varying modulation depth. As expected, and consistent with predictions based on vision science, the stroboscopic visibility was higher for larger modulation depths, for rectangular rather than sine waves, and at higher illuminance levels. The temporal contrast sensitivity function developed from this work showed the peak visibility at 100 Hz and was defined up to 2000 Hz although they observed very low stroboscopic visibility at 800 Hz. This temporal contrast sensitivity function (Perz *et al.*, 2015) was included in a subsequent CIE Technical Note (CIE, 2016) and in test measurement methods published by both the IEC (IEC, 2020) and NEMA (NEMA, 2017). This is the version that has been most widely used, for example by those implementing the EU *Ecodesign* regulation for light sources (European Commission, 2021).

A replication study in China obtained similar results to the early work in Europe (Tu *et al.*, 2013) (this is a rare and welcome example of a cross-cultural test in lighting research). The replication and new data, with conditions up to 1500 Hz and variations in illuminance level, were used together with the original data to develop an updated temporal contrast threshold function (Perz *et al.*, 2018). Although the updated function (which is mathematically very different from the original) was included in the CIE Technical Report 249:2022 (CIE, 2022), it has not yet entered widespread awareness. As the CIE 249:2022 authors themselves noted, further verification of this new function is needed. It would be helpful also to compare SVM values calculated using the two functions and to stroboscopic visibility under varying viewing conditions.

Veitch and Martinsons (2020) tested the stroboscopic visibility for the rotating disc task (i.e., horizontal motion) and a metronome (vertical motion) when lit by one of five commercially available LED replacement lamps with known SVM values (0, 0.4, 0.9, 1.4, and 3.0). Detection of the stroboscopic effect for the horizontal motion was clearly related to SVM, although it was lower than expected for the light sources at SVM = 0.9 and SVM = 1.4. It has been suggested that the difference arose from differences in the experimental method (CIE, 2022). The effects of light source TLM on detection of the stroboscopic effect for vertical motion showed greater variability but for it too, the median detection was higher for the SVM values greater than 1.

Noting that the SVM calculation excludes frequencies greater than 2000 Hz, and wanting also to expand the variations in duty cycles, modulation depths, and waveforms for both stroboscopic visibility and the phantom array effect, a US-based team tested 78 experimental conditions with both tasks (Miller, Rodriguez-Feo Bermudez, *et al.*, 2023), although under conditions of a low adaptation luminance. (The phantom array results are discussed below.) As had been previously observed by both Bullough *et al.* (2011) and Perz *et al.* (2018; 2015), peak sensitivity to the stroboscopic effect occurred around 100 Hz. Rectangular waveforms and waveforms with higher modulation depths showed greater stroboscopic visibility. Both Miller *et al.* (2023) and Vogels *et al.* (2011) appear to show that when considering duty cycle, stroboscopic visibility peaks at 30%.

Miller *et al.* (2023) included the Leiden Visual Sensitivity Scale in their investigation and included in their report a comparison between the high-and low-scoring participants. They found, as predicted, that the high-sensitivity participants rated the stroboscopic effect as more visible than the low-sensitivity participants. The differences were largest for the TLM conditions that were most difficult to see.

4.2.3.3. Phantom array

The phantom array effect occurs as a result of eye movements. It was defined as “change in perceived shape or spatial positions of objects, induced by a light stimulus the luminance or spectral distribution of which fluctuates with time, for a non-static observer in a static environment” (CIE, 2016; 2022). Figure 4.3 shows the effect for a positive-polarity display (illuminated target on a dark background), which is the form that has been most investigated. A more detailed description is available in IEEE 3001.9/IES RP-48-23 (IEEE/IES, 2023): As the eye passes over the light source, it is perceived as a series of spatially extended ghost images rather than a smooth streak. The phantom array is aligned with the saccade trajectory but appears to be entirely displaced on one side of the light source, towards the end point of the saccade. The tail end of the array is virtually coincident with the light source. The multiple ghost images appear sequentially in the reverse direction of the saccade. The multiple images will blur together in different degrees, depending on the waveform characteristics details of the TLM (e.g., its modulation depth, duty cycle, and frequency).

The range over which the phantom array can be detected is large, and there is considerable individual variability. Roberts and Wilkins (2013) found that the average frequency of phantom array detection for the 75% detection threshold was 2470 Hz (note that for the SVM, the researchers used a 50% detection threshold), but one individual had a threshold of 4900 Hz. Brown, Foulsham, Lee and Wilkins (2020), with a slightly different visual task, found an average threshold of 5800 Hz but there were individuals who could detect the phantom array effect at frequencies over 11 000 Hz. Kang, Lee, Lee, and Lee (2023) identified individuals with thresholds in excess of 15 000 Hz. To further explore the reasons for this variability, Kang, Lee, Kim and Pak (2023) varied the visual angle across which the observer scanned. With a wider visual angle, the saccade peak velocity increased, and the threshold phantom array visibility was higher for people with the highest saccade peak velocities.

In Figure 4-3, when an observer scans from left to right across the illuminated line (left half of the figure), what the observer sees will depend on the TLM of the line (depicted on the right half of the figure). With no TLM, the observer sees the image shown at the top right of Figure 4-3. With TLM, the observer sees a striped pattern, as shown in the middle and lower right of the figure, for a higher and lower TLM frequency (Miller and Veitch, 2021).

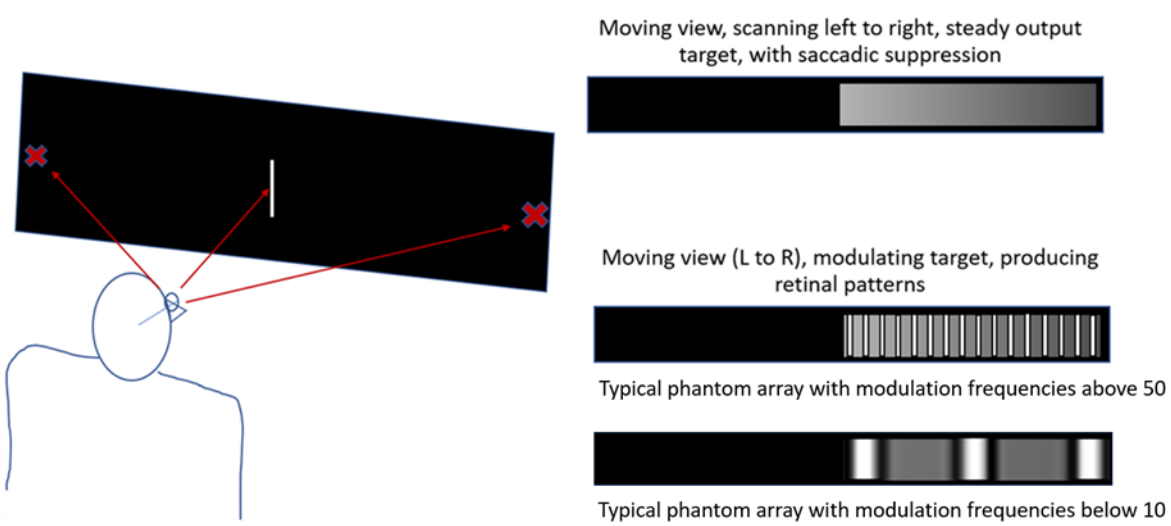

FIGURE 4-3. DEPICTION OF WHAT AN OBSERVER SEES WHEN SCANNING LEFT TO RIGHT UNDER DIFFERENT TLM CONDITIONS

Miller *et al.* (2023), as noted above, studied stroboscopic visibility and the phantom array in a single experiment for a wide range of TLM frequencies (between 90 and 6000 Hz), modulation depths, duty cycles and waveform shapes. The intensity of the phantom array effect was higher for the more sensitive participants. Overall, the peak sensitivity for the phantom array was distinctly different from the peak sensitivity of the stroboscopic effect. For the phantom array the peak occurred between 500 and 1000 Hz (whereas the peak for stroboscopic visibility occurred between 90 – 120 Hz). The SVM was a poor predictor of phantom array visibility, leading them to conclude that a single index cannot explain all visual perception effects of TLM. Evidence from other teams, in both Europe and Asia, has identified 600 Hz as a sensitivity peak for the phantom array when saccades are made across a light target on a dark surface (Kong *et al.*, 2023; Wang *et al.*, 2019). Kong *et al.* determined the visibility thresholds of the phantom array in terms of modulation depth as a function of frequency for three identical stimuli having different colours (red, green, and warm white). At the peak frequency of 600 Hz, the visibility threshold was at 6% modulation depth for the warm-white light.

Light source chromaticity also influences phantom array visibility. Kong *et al.* (2023) observed that peak sensitivity (observed at 600 Hz) was greater for red (visibility threshold of 3.5% modulation depth) than either green (visibility threshold of 7% modulation depth) or warm-white (visibility threshold of 6% modulation depth) light, but there was also an interaction between colour and TLM frequency. Similarly, a team from Korea also found that light source spectrum affects phantom array visibility (Kang *et al.*, 2022). They observed that the phantom array with green light was detected at a higher threshold frequency than the following colours, in decreasing order: warm white, red, cool white and blue (lower threshold frequency). It seems that parameters other than TLM alone will be needed in any predictor of phantom array.

Most investigations of phantom array take place with saccades across a light target against a dark background and under low luminance conditions. Much interest in the phantom array comes from the automotive sector, where it is commonly observed in taillights (Lee *et al.*,

2017). General lighting is, of course, typically at much higher levels and in most interiors (and for most reading) observers scan dark targets on a light background. This is not typical of general lighting. Wang *et al.* (2019) included an experiment in which observers looked at a dark target on a white background, with horizontal illuminance of either 250 lx or 500 lx, for one TLM condition: a sine wave with 600 Hz, 100% modulation, for 10 trials in a two-alternative forced choice method in which for each trial the alternative was a no-TLM [DC] condition. They found that the detection probability for this condition was approximately 70% for both illuminance conditions, whereas for that experimental method threshold viewing is a 75% identification rate. They concluded that under most interior conditions the phantom array is unlikely to be problematic for most viewers. There was, however, a large variability between individuals. Given the evidence for the effect of saccade speed and light source spectrum on phantom array detection, it might be premature to exclude the possibility of phantom array experiences in general interior lighting.

4.2.4. Task performance

The evidence from legacy lighting systems shows that the 100 Hz and 120 Hz TLM from magnetically ballasted lighting systems can reduce visual and cognitive task performance in comparison to performance under electronically ballasted fluorescent lighting systems. These investigations had participants from the general population, and effects were not easy to detect. The effects were seen in difficult tasks and in experiments with large sample sizes and long exposures. For example, Veitch and McColl (1995) found that visual performance was worse under magnetic ballasts, but only for very difficult targets and in a repeated-measures design with young participants. An attempt to replicate the effect with a between-groups design and a wide range of participant ages did not lead to statistically significant results (Veitch *et al.*, 2002).

By contrast, Veitch and Newsham (1998) conducted a between-groups experiment with a sample of 292 participants found that working under electronic ballasts led to typing longer words and more characters overall during a creative writing task, and attempting more questions on a reading task, than working under magnetic ballasts. On a computerized reaction time task, they performed faster and more accurately when the space was lit with electronic ballasts, and this effect interacted with task complexity; the best performance was for simple tasks under electronic ballasts. Similarly, visual performance on a Landolt ring task was better for a difficult visual task (low contrast targets) under electronic ballasts than magnetic ballasts. These effects are all consistent with previously discussed evidence that TLM disrupts eye movements, marking reading more difficult (see section on brain activity and neurology).

Performance disruptions to tasks involving reading have been reported elsewhere: Küller and Laike (1998) found that the high-CFF (sensitive) participants performed a proofreading task faster and with a higher error rate under magnetic ballasts than electronic ballasts. Similarly, in two experiments young participants showed better performance of a visual search task when the lighting was from fluorescent lighting with electronic ballasts than magnetic ballasts (Jaén *et al.*, 2011; Jaén *et al.*, 2005). Both experiments had repeated-measures designs; the first (Jaén *et al.*, 2005) had 50 participants, but the second had only 12 (Jaén *et al.*, 2011). In none of these studies did participants report visual perceptions related to TLM: that is, the TLM was not perceptible.

Rarely, other tasks have been employed. Knez (2014) contrasted magnetic and electronic ballasts, examining effects on mood, attention, memory, and problem-solving. He found a main effect in which participants felt more pleasant after a period of working on the memory and problem-solving tasks under electronic ballasts than magnetic ballasts. The attention, memory and problem-solving tasks did not show statistically significant differences between lighting conditions.

Turning to evidence from LED lighting systems, reading tasks also show diminished performance under conditions with greater TLM, but not for all tasks nor all statistical comparisons. The inconsistencies arise in part from the many possible variations in experimental conditions. For example, TLM at 100 Hz and 100 % modulation depth with rectangular waves led to more proofreading errors in comparison to 1000 Hz (Bullough *et al.*, 2013). Their paper did not report planned comparisons between conditions, but it appears that there was no difference between 100 Hz / 25% modulation depth and 1000 Hz / 100% modulation depth. Veitch (2019) did not detect an effect on reading performance in a comparison between TLM in a 120 Hz rectified sine wave of 30% modulation depth and 1000 Hz in a rectangular wave of 30% modulation depth. Nilsson Tengelin and colleagues (2017) varied TLM in very complex ways using combinations of light sources that make it difficult to characterise the total stimulus; they did, however, report that conditions with more TLM disrupted attention on a visual search task.

Veitch *et al.* (2024), in a sample of young people, found no effect of TLM on sentence reading speed. They did, however, find that the Stroop cognitive interference effect was greater for 100 Hz than 500 Hz TLM (both rectangular waves with 100% modulation depth and 50% duty cycles); there was no difference between the no-TLM condition and the 100 Hz condition. In a second experiment that was nonetheless published first, Veitch (2019) contrasted no-TLM and 500 Hz rectangular waves (100% modulation depth, 50% duty cycle) in an attempt to replicate the effect on Stroop cognitive interference. The effect did not, however, replicate (Veitch, 2019). Veitch and Miller (2024) re-analysed this data for subgroups based on pattern glare sensitivity. There was a main effect of pattern glare sensitivity on the Stroop cognitive interference effect in which the high sensitivity group showed stronger cognitive interference than the low-sensitivity group. In the high sensitivity group, modulation depth influenced the speed of Stroop performance, with a small effect of faster performance for 15% modulation depth than 30%, both at 500 Hz. For the low-sensitivity group a pair of conditions at 1000 Hz revealed a large effect of greater cognitive interference for 100% modulation depth than 30%.

Taken overall, the literature shows that TLM can influence tasks that involve reading. Detecting these effects requires careful attention to research design and the details of the procedure and participant characteristics. A few studies have examined individual differences and have observed variations in responses to TLM in groups differing in sensitivity. General conclusions remain elusive because of differences in experimental conditions and incomplete or unusual reporting that prevents comparisons between studies.

4.2.5. Acceptability and comfort

Prior to the introduction of electronic ballasts for fluorescent lighting systems, complaints about eyestrain and headache in workplaces were common (Lindner and Kropf, 1993; Stone, 1992). There are several possible reasons for these complaints, including poor colour rendering, glare, veiling reflections (particularly after the introduction of desktop computers

with cathode-ray-tube monitors), and TLM from magnetic ballasts. An early attempt to isolate what we now would call TLM as the cause compared ratings of the room appearance and lighting adequacy from a sample of men who worked for half a day each under fluorescent lighting with a 50 Hz AC (magnetic) ballast (100 Hz TLM), or a DC ballast (no TLM), in a counterbalanced order (Brundrett *et al.*, 1973). They found no evidence of a preference for one lighting condition or the other and concluded that if care was taken to exclude flicker (that is, the perception) then both systems would be adequate.

Over a longer-term exposure, however, the influence of lighting system TLM on headache became clearer, and visual perception of the TLM was seen to be unrelated to headache incidence. Wilkins, Nimmo-Smith, Slater and Bedocs (1989) conducted a double-blind cross-over field intervention trial, comparing magnetic and high-frequency electronic ballasts, over several weeks in each condition. They found that the overall incidence of headaches was lower under the electronic ballasts. Perception of TLM was not a factor: Indeed, participants showed little awareness that there had been lighting changes, and were inaccurate in identifying when changes might have been made. Individual differences in sensitivity did matter. Most people had no headaches under either condition, but people who reported frequent headaches under magnetic ballasts had much less frequent headaches under the electronic ballasts. Wilkins *et al.* (1989) also observed that the electric lights were on for less time with the magnetic ballasts than the electronic ballasts, in what could be an indirect indicator of preference.

These historical studies reveal that there may be effects of TLM on physical symptoms irrespective of any visual perception effects, and that a portion of the population might experience these ill effects more than others, but they also show that very careful research design and realistic exposure times may be necessary to achieve results that are causally convincing. Moreover, investigations with legacy light sources cannot provide the detail needed for guidance on LED light sources and lighting systems.

Bullough *et al.* (2011), in studying both flicker and the stroboscopic effect, included a question about the comfort under each condition. The exposures were very short (eight conditions experienced in a session under 30 min long) and there were only 10 participants. Participants reported discomfort for conditions with a frequency of 60 Hz or less, but comfort at higher frequencies. A later experiment with a wider range of conditions, but still very short exposures and only 10 participants (possibly some of the same individuals), was the basis for empirical model development (Bullough *et al.*, 2012). Distinctly different models based on frequency and modulation depth predicted stroboscopic visibility and acceptability (comfort was not rated in this experiment). Participants rated acceptability on a scale from -2 (very unacceptable) to +2 (very acceptable); the mean acceptability rating was equal to or below 0 for the combinations 100 Hz and either 100 % modulation depth or 54% modulation depth, and 300 Hz and 100% modulation depth.

Having developed the SVM to predict detection of the stroboscopic effect, Perz, Sekulovski, and Beeckman (2017) sought to use the SVM to predict acceptability of the TLM conditions. They reported a combined dataset from four experiments, each undertaken with varying numbers of experimental conditions and a combination of participant samples in which some people saw more experimental conditions that others. Their merged data were fit to a logistic function. Noting that satisfying all people is unlikely, they suggested a criterion of satisfying

at least 80% of the population, which for their data corresponded to SVM = 1.5. Their interpretation of the acceptability threshold reported by Bullough *et al.* (2012) showed approximate agreement despite the considerable difference in experimental methods between the two.

The SVM perception experiment by Veitch and Martinsons (2020) included ratings of acceptability and annoyance on the last of 10 trials for each of the five light sources. Data were collected with different light sources matched for SVM in Canada (in English) and France (in French). Ratings of annoyingness were lower in France, which seemed most likely to be a problem of translation. Nonetheless, ratings of annoyingness were higher overall light sources for people who were more sensitive to pattern glare, as assessed with the Wilkins and Evans Pattern Glare test (Wilkins *et al.*, 2010). Over the whole sample (both countries and regardless of sensitivity), the light sources with SVM = 0.9 were rated as more annoying than those of SVM = 0.4. This is striking particularly for the very short exposures (less than a minute for each trial).

Another approach to understanding discomfort is to return to fundamentals of vision. Noting that there is evidence that in the spatial domain patterns that deviate from natural image statistics (1/frequency) are uncomfortable and can be triggers for seizures in people with photosensitive epilepsy (Fernandez and Wilkins, 2008), Yoshimoto and colleagues examined whether the same might be true for temporal variations in amplitude spectrum (Yoshimoto *et al.*, 2017; Yoshimoto *et al.*, 2019). Over two laboratory experiments, they found that both the amplitude spectrum and the waveform (rectangular vs random phase spectrum) influenced discomfort, with the results being further complicated by different effects of adaptation to the stimulus for various experimental conditions. This line of research has yet to be translated into the models developed by applied lighting researchers but offers the potential for the development of a new indicator to predict discomfort.

As for concerns with modulation depth or rectangular waves, there is mixed evidence concerning the observer experience depending on the question asked and, likely, on experimental methods. Veitch (2019) reported a paradoxical effect in which discomfort ratings were higher for a condition with 30% modulation depth than 100 % modulation depth (both 500 Hz, 50% duty cycle). Zhao *et al.* (2020), by contrast, reported greater self-reported fatigue for conditions with 70% modulation depth than 30% (averaged across frequencies).

It seems likely that individual differences in sensitivity matter to visual comfort. Everyday visual discomfort was highest for those whose phantom array detection thresholds were highest when tested by Brown *et al.* (2020). Whereas Veitch (2019) reported no effect of duty cycle on visual discomfort in the full sample (N=50), Veitch and Miller (2024) re-analysed the same data to examine matched subsamples formed on the basis of high and low pattern glare sensitivity. They found that for a subset of high-sensitive individuals (N=13), discomfort was higher for the 30% duty cycle than the 50% duty cycle. This was a medium-sized effect, and arose after an approximate 17 min exposure to each condition.

To date, we see one field investigation with LED lighting systems in an experimental design similar to the Wilkins *et al.* (1989). Sekulovski, Poort, Perz, and Waumans (2020) compared two lighting conditions in a crossover design in occupied workspaces (and office and an electronics workbench) over a three-month period. Both lighting conditions showed

sinusoidal TLM with 100 Hz as the dominant frequency, but the reference condition had 12.5 % modulation depth (SVM = 0.47) and the intervention condition had 36.4% modulation depth (SVM = 1.34). Participants completed daily online surveys about physical symptoms and mood on testing days. Overall, the investigation showed no differences in physical symptoms or mood as a result of the changing light exposures. The authors concluded that it would be acceptable for workplace lighting to exhibit the TLM characteristics of the intervention condition, which interestingly approximate the TLM associated with magnetic ballasts. Others have observed that this is not a conclusive result because the workspaces had large south-facing windows on the long axis of the room, which would have reduced the contribution of the electric lighting to the space, thereby reducing the overall TLM for the combined office lighting and daylight and mitigating the TLM exposure, especially for the locations nearest the windows (Veitch *et al.*, 2021). Furthermore, these findings for the averages of the sample of 46 individuals could mask more important effects on a sensitive subpopulation.

4.3. Conclusions

Some might argue that if the observer cannot report flicker, then there is nothing to worry about (e.g., Brundrett *et al.*, 1973). This belief is founded on the belief that only those conditions that reach conscious awareness can harm us. Neuropsychology shows, however, that there are many visual phenomena that reveal a separation between perception and conscious awareness (Naccache, 2009) – that is, there are stimuli detected at the retina and processed by the visual cortex, but that the observer cannot verbally report. Researchers use indirect behavioural measures and functional imaging techniques to identify these phenomena. In the case of TLM, there is ample evidence that temporal fluctuations in light stimuli affect human physiology and behaviour, with implications for health and well-being. Table 4.1 summarizes the preceding literature review and identifies some of the gaps in the literature.

The emerging logical chain is this:

- TLM is photochemically detected at the eye.
- Modulated neural signals reach the brain; they are neural noise, not contributing information to the visual image.
- Processing this neural noise takes cognitive resources, increases brain activity and blood flow.
- The neural noise includes competing information that disrupts saccades, interfering with visual performance.
- The neural noise can give rise to visual perceptions (flicker, stroboscopic effect, phantom array effect).
- The increased cognitive load together with the disrupted eye movements affects cognitive performance.
- The increased physiological effort required can manifest in eyestrain, headache, and fatigue, particularly over longer periods.
- Sensitive individuals might react sooner and/or more intensely, or experience more serious consequences such as migraine and photosensitive epileptic seizures.

4.4. Recommendations

It is no longer a question of whether TLM affects observers, but of what range of conditions ought to be permitted. Expert stakeholders had hoped that a single quantity might predict many outcomes (CIE, 2017), but that now seems unlikely, given the emerging data for the phantom array effect as compared to the stroboscopic effect. Researchers will need to use strong research designs and pay attention to the validity and reliability of behavioural measures in order to determine the range of conditions that best supports the population.

At the time of writing, there are no indexes to predict behavioural outcomes other than flicker detection and the stroboscopic effect. P_{st}^{LM} has several weaknesses as a predictor of flicker (noted above), but could be replaced by an updated M_P, among whose strengths is the fact that it takes account of frequencies up to 90 Hz. SVM (quantity symbol M_{VS}) is a reasonable predictor of the stroboscopic effect. Understanding that these might later be augmented (or perhaps replaced) by other quantities, it nevertheless is reasonable to use these indices to set limits on permissible TLM conditions with the intent of limiting the potential for adverse effects on viewers, especially sensitive individuals.

There is a specific need to target dimmable lighting systems, which are increasingly common as part of dynamic lighting and daylight-linked control systems. PWM is the most common form of dimming for LED products, and often introduces rectangular wave TLM to the light output. Rectangular waveforms show consistently show the most problematic outcomes for observers. Even in the limited jurisdictions that regulate light source TLM (California Energy Commission, 2023; European Commission, 2021), the regulations do not apply to products at other than full power. This should make a focus on rectangular waves across the common range of PWM frequencies and modulation depths the most urgent research priority.

TLM criteria that apply only at full power leave observers unprotected from TLM that occurs when the light source is dimmed, but dimming is an important tool for lighting energy savings. Further engineering research will be needed to understand the challenges of driver and dimmer compatibility in order to eliminate combinations that cause TLM to occur when the light source is dimmer but not when it is at full power.

The risk of problematic TLM would be reduced if lighting systems were designed to produce more continuous wave shapes and to avoid rectangular waves. Driver and dimmer electronics that combine constant current reduction, pulse frequency modulation and pulse width modulation dimming techniques appear to be most promising in this regard (Miller, Rodriguez-Feo Bermudez *et al.* 2023).

TABLE 4-1. SUMMARY OF EFFECTS OF TLM AND RESEARCH GAPS

Category	TLM exposure effects	TLM conditions / quantity	Knowledge gap

Light sensitivity	A subset of the population experiences
	• Visual stress: headache, eyestrain
	• Migraine
	• Epilepsy
		• Specific triggers per sensitive individual
		• Diagnostic tests:
		  ○ Pattern Glare Test (Wilkins and Evans, 2012)
		  ○ Leiden Visual Sensitivity Scale (LVSS) (Perenboom *et al.*, 2018)
			• Population norms for the LVSS

Brain activity and neurology	• Increased brain activity • Increased physiological arousal • Increased cortical blood flow • Disrupted eye movements • Seizures or migraines in sensitive individuals	• Frequency is the most important parameter • 3 Hz to 70 Hz range for seizure risk • 100 Hz and 120 Hz disrupt eye movements	• Most comparisons include a 100 or 120 Hz condition; there is limited evidence for stimuli between 100 Hz and 1000 Hz, which is the operating range for most PWM dimming systems.

Visual perception	• Flicker
	• Stroboscopic effect
	• Phantom array
		• Flicker: 0 – 80 Hz, peak between 15-20 Hz
		  ○ Quantity: P_{st}^{LM}
		• Stroboscopic effect, 80-2000 Hz, peak ~ 90-120 Hz
		  ○ Quantity: SVM
		• Phantom array, peak ~600 Hz but visible up to several kHz by sensitive individuals
		• More visible with rectangular than sine waveforms
		• Variations with modulation depth and duty cycle
		• More visible to sensitive individuals
			• Flicker needs a better predictor: P_{st}^{LM} might underpredict flicker perception; the calculation filters out frequencies above 35 Hz. It has not been validated against human perception data, including not for varying contextual conditions (e.g., low adaptation luminance, peripheral viewing…)
			• SVM has a new temporal contrast sensitivity. function, requiring validation.
			• There is no quantity to predict the phantom array.

Task performance	• Poorer visual performance for difficult tasks • Slower and less accurate reaction time performance, especially on difficult tasks • Reduced performance on tasks requiring reading • Increased cognitive interference	• 100 Hz / 120 Hz worse than 20,000 – 40,000 Hz (electronic ballasts) • 100 Hz worse than 500 Hz • More sensitive individuals might show larger effects.	• Limited evidence for TLM with rectangular waves between 100 – 1000 Hz, where PWM dimming systems operate. • Effect sizes are small, requiring tight experimental control.
Comfort and acceptability	• Anecdotal reports of headache and eyestrain, especially from sensitive individuals • Discomfort from headache and eyestrain • Individual sensitivity	• 100 Hz / 120 Hz worse than 20,000 – 40,000 Hz (electronic ballasts) • For rectangular waves, an apparent peak for 30% duty cycle • Deviations from natural images, both amplitude and waveform	• Long term data from PWM-dimmed systems • Focus on sensitive population • Experimental design and analysis to maximize effect size

5. Circadian Effects

5.1. Introduction

Light enters through the eye and stimulates specialized cells in the retina called photoreceptors. In humans, the vast majority of photoreceptors that contribute to vision are known as rods and cones. In the 1990s and early 2000s, photobiology was revolutionised by the identification of a new class of photoreceptors, the intrinsically photoreceptive retinal ganglion cells (ipRGCs) (e.g., Berson, Dunn and Takao, 2002; Hattar *et al.*, 2006; Provencio *et al.*, 2000). It was apparent that stimulation of these cells at night reduced secretion of the pineal hormone melatonin. An action spectrum that described the melatonin suppression response of these cells to different wavelengths contributed to demonstrating that these cells are not the same as the rods or cones, and that their peak sensitivity is in short wavelengths between approximately 460 and 490 nm {Brainard *et al.*, 2001; Thapan, Arendt, and Skene, 2001}. These 1% of cells in the retina project to many brain areas and influence many functions, but not vision (Fernandez, 2022). These so-called ipRGCs are most sensitive to short wavelength light (480 nm) and communicate to the suprachiasmatic nucleus (SCN) located within the hypothalamus of the brain.

Measuring light with the usual photopic quantities, which are weighted by the *V(λ)* spectral luminous sensitivity function, does not give an accurate indication of the intensity of ipRGC exposures. The CIE standard S026:2018 (CIE, 2018) defines the spectral sensitivities of five classes of photoreceptor: the rods (rhodopic), the short-, medium-, and long-wavelength cones (S-cone-opic, M-cone-opic, and L-cone-opic), and ipRGCs (melanopic) sensitivity functions (Figure 5.1). The standard also defines metrologically correct SI quantities for these five *α-opic* functions (α being the generic form, and one substitutes the appropriate prefix for a specific quantity).

To facilitate comparisons, the standard further provides a scaling function to relate the given light source to the CIE D65 illuminant, which is an accepted model for daylight with a CCT of 6500 K. The CIE recommends to report the *α-opic* equivalent daylight illuminance (EDI), which is the equivalent amount of D65 exposure, in lx, to the quantity of the light source being described. A related quantity, the *α-opic* daylight efficacy ratio (DER) is the ratio of the *α-opic* efficacy of luminous radiation for the test light source to the *α-opic* efficacy of luminous radiation for the CIE D65 illuminant. One can use this value to compare spectra, independent of the intensity of illumination.

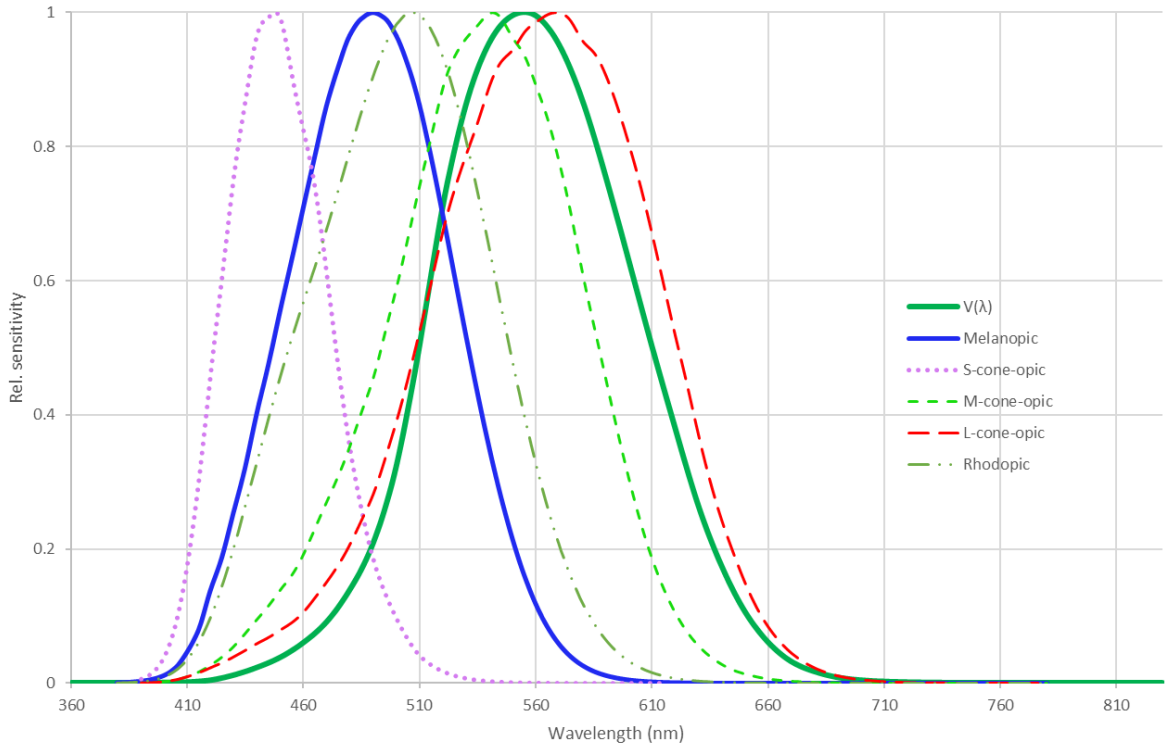

FIGURE 5-1. THE FIVE ALPHA-OPIC SPECTRAL SENSITIVITY CURVES, AND THE V(Λ) CURVE USED IN PHOTOPIC MEASUREMENTS

Using appropriate quantities to describe light exposure and measuring the exposure in the plane of the eye in the direction of gaze is a substantial change to previous practice, but is very important to the accurate determination of the conditions to which people have been exposed. Older research in this field could not, of course, follow these practices; nor do all investigators do so today. In this review, we have had to report light measurements in the way that researchers reported them, which may limit the comparability of findings from one study to another.

5.2. Effects of light exposure on the biological clock

The research that led to the discovery of the ipRGCs also established that light is the strongest of the stimuli that influence human circadian rhythms. 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 ipRGCs communicate to the SCN located within the hypothalamus of the brain. The SCN is referred to as the 'master clock' and is responsible for synchronizing circadian rhythms. Exposure to light activates receptors in the SCN and this is how entrainment to the 24-hour day/night cycle occurs. This pattern probably evolved because of to the natural light-dark cycle (i.e., sunrise and sunset) and electric lighting can result in disruptions to the circadian system.

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. For example, short wavelength light in the evening (especially blue light wavelengths), signals the SCN to suppress the release of melatonin (a hormone produced by the brain in response to darkness that helps with the timing of circadian rhythms and sleep) from the pineal gland, thereby delaying sleep onset. This demonstrates one common way inappropriately timed light exposure influences human health by disrupting circadian rhythms and disturbing sleep onset.

A phase response curve was published by Khalsa *et al.* (2003) and demonstrated that light exposure in the evening, before the core body temperature minimum (i.e., approximately 1-2 hours before habitual wake time) delays the circadian clock, while light exposure after the core body temperature minimum, in the morning, advances the circadian clock. This relationship between light exposure and circadian rhythm delay or advance is non-linear, for instance, Chang *et al.* (2012) showed that a short evening light exposure (starting at approximately 2:30 am) of only 12 minutes at 7,669 lux (4100 K light source) delayed the circadian clock (measured via plasma melatonin) by approximately 1 hour, while a much longer light exposure of 4 hours (starting at 12:30 am) at a similar intensity (8,396 lux) delayed the circadian clock by approximately 2.5 hours. As such, the duration of 12 minutes was over five-times more effective at delaying the circadian clock. It is also important to note that circadian rhythms change across the lifespan, with adolescents more likely to experience circadian phase delays, while the opposite seems to be true for older adults who are more likely to experience advances in circadian timing, and therefore the effects of light exposure on circadian rhythms may differ across different populations (Hagenauer *et al.*, 2009 and Duffy *et al.*, 2015).

5.3. Effects of light exposure on sleep

The relationship between circadian rhythms and sleep timing is well-established, which has sparked research into how light affects sleep. Light in the evening, particularly in the blue spectral region suppresses melatonin (Fernandez, 2022; Prayag *et al.*, 2019; Tähkämö *et al.*, 2019), which increases the core body temperature (Gomes and Preto, 2015; te Kulve *et al.*, 2016) and heart rate (Chellappa *et al.*, 2017; Gomes and Preto, 2015), and ultimately can lead to delayed sleep onset (Fernandez, 2022). However, the findings regarding how light influences core body temperature and heart rate are less conclusive (Wang *et al.*, 2022). 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 (Cajochen *et al.*, 2022; Vetter *et al.*, 2022). Other research suggests that evening light exposure can reduce sleep efficiency and rapid eye movement sleep (Cajochen *et al.*, 2022; Chellappa *et al.*, 2017; Cho *et al.*, 2016; Tähkämö *et al.*, 2019), but these findings are less conclusive.

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 (Fernandez, 2022; Prayag *et al.*, 2019; Vetter *et al.*, 2022). 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 (Fernandez, 2022; Lu *et al.*, 2019; Prayag *et al.*, 2019; Stefani and Cajochen, 2021).

5.4. Effects of light exposure on metabolic functions

Aside from the relationship between light and the circadian system/sleep, the relationship between light and thermal physiological effects is mixed. Some research suggests that light exposure has important implications for cardiovascular health, however limited causal evidence exists (te Kulve *et al.*, 2016). One study by Cajochen *et al.* (2005) found a 2-hour exposure to monochromatic blue light in the late evening increased heart rate compared to monochromatic green light. More research is needed to clarify any link between morning or evening light exposure and heart rate, cardiac function, and body temperature.

5.5. 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 (Gomes and Preto, 2015). Alternatively, adolescents are found to have greater melatonin suppression from blue light compared to adults (Fernandez, 2022; Grubisic *et al.*, 2019). Consistent evidence has shown lighting stimuli also evokes a stronger melatonin suppression in children compared to adults (Westwood *et al.*, 2023). Despite this, the effect of light on melatonin does not always translate into sleep outcomes as the evidence for the effect of light on children's sleep is limited and suffers from inconsistencies in lighting exposure and methodological rigor (Westwood *et al.*, 2023). However, it has been shown in young children that light exposure in the evening may be associated with a later sleep onset (Ulset *et al.*, 2021) whereas exposure to bright light in the early afternoon may be associated with more consolidated sleep (Harrison, 2004).

5.6. Effects of light interventions

It is important to note the use of lighting interventions may also be beneficial to some populations. For example, older adults are often exposed to limited bright light during the day.

Lighting interventions may provide a useful avenue for increasing daytime bright light exposure while minimizing evening light, which could improve circadian synchronization to the light-dark cycle and improve sleep quality. In these cases, indoor daytime light should be at least 1,750-3,000 photopic lux (Figueiro and Leggett, 2021; Hood *et al.*, 2004; Perdahci and Yuce, 2019), however some contradictory evidence exists (Friedman *et al.*, 2009). Generally, most lighting interventions increase light exposure duration for lower intensity light and use shorter durations (e.g., 30-60 minutes) for high light intensities (>10,000 photopic lux) (Zhang *et al.*, 2023). A recent systematic review of light interventions in older adults found positive results for studies measuring sleep outcomes.

For example, three studies on residents of long-term care settings demonstrated more consolidated sleep during the night following morning light therapy (2,500 lux for 2 hours or 6,000-8,000 photopic lux for 30 minutes to 2 hours) from a light box (Zhang *et al.*, 2023). Despite these apparent benefits, the evidence base lacks homogenous assessments of the effectiveness of light therapy in older adults, and more research is needed.

Shift workers are another population where lighting interventions may be beneficial so that nighttime light exposure is low enough to avoid delaying their circadian rhythm yet bright enough to allow work to be performed safely (Lowden and Kecklund, 2021). In shift workers, bright light therapy (ranging 1,500 to 10,000 photopic lux) can be used alone or in combination with glasses to filter short wavelengths (e.g., to limit blue light exposure before sleep), and was shown in a recent systematic review to improve sleep outcomes in all nine interventions reviewed (Jeon *et al.*, 2023). However, these authors made no recommendations for the timing and duration of the light interventions, and the evaluated studies varied in these components.

Finally, it is important to note that different light sources may influence the circadian system differently. Ashena *et al.*, (2022) reviewed the predicted melatonin suppression based on past studies and demonstrated how different light sources may influence melatonin, which may subsequently impact sleep. For example, 138 lux of daylight is required to suppress melatonin by 25%. To achieve the same suppression, 302 lux from a fluorescent light source (3,350 K) is required, particularly as fluorescent light contains less blue light compared to natural light sources (Gomes and Preto, 2015). Furthermore, only 13 lux is required from an LED light source to suppress melatonin by 25% (Ashena *et al.*, 2022). Therefore, it is important to consider the light source when considering implemented lighting inventions.

5.7. Daily light exposure consensus report

Using melanopic EDI as the exposure index for describing light exposure, expert consensus (Brown *et al.*, 2022) suggested that daytime light exposure should be above a melanopic EDI of 250 lux, measured at the plane of the eye. The best way to achieve this is using daylight, but if that is not available then electric lighting should be rich in white light with a wide spectral distribution including components at all visible wavelengths.

To avoid activation of the ipRGCs and thereby reduce the influence of light on the circadian system and sleep, light with longer wavelengths (i.e., yellow, orange, and red colours) should be used in the evening and nighttime. From at least 3 hours before sleep, the melanopic EDI should be lower than 10 lux and lower than 1 lux when attempting to sleep (Brown *et al.*, 2022). It is important to note that these guidelines apply for adults sleeping at night and special considerations are needed for shift workers, children, older adults, and other populations that differ from healthy adults. For example, older adults may benefit from more daytime exposure while children may benefit from less evening exposure (Brown *et al.*, 2022).

There remain open questions about using melanopic quantities such as melanopic EDI measured in the plane of the eye (i.e., at the cornea) as criteria for circadian regulation and other non-visual effects. For instance, the interplay of different photoreceptors influences pupil size and this determines the amount of light reaching the retina (Spitschan, 2019). The spatial distribution of light in the field of view relative to the distribution of ipRGCs across the retina is another topic of some debate (Zauner, Broszio, and Bieske, 2023). Nonetheless, overall, the majority of research suggests that melanopic EDI is a reliable index that can be used to provide a good estimate of the effects of light exposure on circadian rhythms and non-visual health outcomes (Brown *et al.*, 2022).

5.8. Conclusions

Depending on the timing, amount, direction 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. Effects of light on metabolic functions are less clear, and more research is needed before any conclusions can be drawn. Exposure assessment is extremely important, and melanopic EDI provides an exposure index that can be used to reduce unwanted effects of light on circadian rhythms, sleep, and associated health outcomes.

It is important to note that this information largely pertains to healthy, day-active individuals, and how or if the impact of light exposure may differ among potentially sensitive populations, such as children, the elderly, or shift workers, is less clear.

Research on the effects of light exposure on children's sleep remains sparse, and given the importance of sleep for development, this constitutes an important future research need. Likewise, more research specifying clear lighting intervention guidelines for older adults and shift workers is needed to provide optimal lighting environments to improve their sleep and strengthen circadian rhythms.

5.9. 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 or more intense light during the morning and daytime could have beneficial effects by decreasing the sensitivity of the circadian rhythm to light in the evening.

Given that it is well established that a healthy pattern of light and dark every day is necessary for good health, all lighting recommendations should reflect the need to deliver this pattern. Doing so in an energy-efficient manner might involve using a higher proportion of shorter-wavelength light during the day to increase the effective exposure with less energy and emphasizing longer wavelengths at a lower intensity in the evening to maintain a lower exposure. The choice of light source spectrum and intensity, however, must balance other lighting goals; lighting recommendations that integrate the various purposes of a lighting installation are to be preferred over documents that target only circadian regulation, or visual performance, etc. For the time being, until further information accrues, the target daytime illuminance could be set at 250 lx melanopic EDI at the eye; for evening, 10 lx melanopic EDI at the eye or less; during sleep, 1 lx melanopic EDI at the eye or less.

Some populations may require different lighting conditions to optimize their circadian rhythms and sleep. For instance, 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. Very special attention is

needed for people who have little freedom of movement, who cannot choose their own light exposures, such as hospital patients, residents in long-term care, and those held in detention centres, jails, or prisons.

Most people spend time in a variety of places over the day, and therefore achieving the healthful pattern of light and dark is often a matter of personal responsibility. Therefore, public health agencies and departments alongside energy and industry regulators and lighting suppliers should work together to promulgate information about the best way to use light to benefit health. This is a problem of communication as well as possibly of regulation.

6. Acute Neuro-behavioural Effects

6.1. Introduction

In this chapter, we consider how light exposure influences cognition and well-being, largely without reference to effects on circadian regulation or sleep (which were covered in the previous chapter). Cognition encompasses any effect on the ability to process information (e.g., attention, memory, perception), including acute alerting effects. We define well-being broadly, including mood, satisfaction, and social cohesion. The underlying mechanisms by which these effects occur remain to be fully disentangled, however, there appear to be direct (i.e., immediate, acute) and indirect (i.e., delayed) mechanisms at play, possibly involving the ipRGCs either alone or in combination with other retinal photoreceptors ("ipRGC-influenced effects of light, or IIL, per the CIE (CIE, 2018)). Effects that are primarily visual (e.g., visual appearance) are out of scope for this report because they are application dependent.

In keeping with scientific consensus about light exposure parameters, this chapter summarizes the state of knowledge concerning cognition and well-being effects in terms of the intensity (irradiance, illuminance), spectrum, duration, timing, and pattern of exposure (Cajochen, 2007). As described in section 5.1, intensity and spectrum can be used to calculate the appropriate quantities to describe the exposure to each of the five photoreceptor classes (CIE, 2018). The effects of light for different sub-groups, such as shift-workers, along with the effects of light beyond the visual spectrum, will be discussed briefly. The literature concerning this topic is vast, and therefore this chapter takes a "review of reviews" approach, supplemented by individual studies that are recent enough not to have appeared yet in review papers.

6.2. Intensity

6.2.1. Alertness and Cognition

The intensity of lighting exposure has been most-widely studied in relation to alertness and cognition; it is the easiest parameter to change experimentally and is also of interest in the context of lighting energy use. Anecdotally, higher illuminance increases alertness and task performance, although one meta-analysis found that this effect when measured with reading performance disappeared following an adaptation period (Gifford *et al.*, 1997).

Historically, researchers characterised light exposures only in photopic illuminance, because it was the only quantity available. With the publication of CIE S026:2018 (CIE, 2018), researchers are recommended to report five quantities, one each for the five known photoreceptor types, (collectively known as the α-opic quantities, see section 5.1), with the equivalent daylight illuminance being the preferred quantity. Much attention has focused specifically on melanopic quantities, which describe the action of the intrinsically photosensitive retinal ganglion cells (ipRGCs), because of the many brain regions to which these cells project and because of the known effects of ipRGC stimulation on night-time melatonin and circadian regulation.

Measurements in the plane of the eye in the direction of gaze, furthermore, provide information about the observer's exposure (CIE, 2004/2009; 2018), whereas the more common horizontal illuminance on a working plane measurements provide limited information about light exposure. These practices reduce the value of the older literature to inform contemporary lighting practice.

Studies in this area have used physiological (e.g., heart rate variability, brain activity), behavioural (e.g., reaction time), and self-report (e.g., the respondent's feeling of being awake) indicators of alertness and task performance. The results are mixed.

Hommes and Giménez (2015) combined the results of eight studies for which the Karolinska Sleepiness Scale had been used as the measure of alertness (sleepiness), some of them in daytime and some at night. They found that melanopic illuminance (as defined by Lucas *et al.* (2014)) was a better predictor of the change in sleepiness following an exposure period (usually 2 hours or more) than photopic illuminance, with the maximum effect occurring at approximately 900 lx melanopic equivalent daylight illuminance (converted from the 1000 lx reported in (Hommes and Giménez, 2015) using the conversion provided by Schlangen and Price (2021)). Brown (B 2020) included 19 studies in a similar meta-analysis, with similar conclusions as to the predictive value of melanopic illuminance (reported as melanopic EDI), but an apparently somewhat lower level for the plateau, which he attributed to methodological factors.

Three review papers published in the past ~5 years have concluded that there is no conclusive evidence that increased light intensity has a direct, immediate effect on alertness when measured physiologically and or with cognitive task performance (Alwalidi and Hoffmann, 2022; Lok, Smolders, *et al.*, 2018; Souman *et al.*, 2018). Both Lok, Smolders *et al.* and Souman *et al.* concluded that self-report measures of alertness show the most consistent results, but they do not translate into substantial, statistically significant performance effects, a conclusion echoed in Alwalidi and Hoffman, (2022) and Siraji *et al*. (2022).

Konstantzos, Sadeghi, Kim, Xiong, and Tzempelikos (2020) noted the importance of separating studies in which task performance effects occur because of improvements in visual performance with higher light levels. They judged that improved task performance was observed in most studies with increases in illuminance. All the review papers identified several research design limitations that have limited the conclusiveness of this body of research.

One meta-analysis found that there was a statistically significant effect of "daytime electric light" exposure on cognitive performance in which a larger exposure led to a small improvement in cognitive performance (Li *et al.*, 2023). Unfortunately, however, the analysis did not examine whether there is a dose-response relationship; the authors used a categorical coding system comparing intervention and control conditions, and also mixed studies without regard for spectral differences in the exposures.

Siraji *et al.* (2022) identified an interaction effect of task complexity; effects differed for simple and complex tasks. This is broadly consistent, as they noted, with the Yerkes-Dodson relationship between arousal and performance (Yerkes and Dodson, 1908), in which the optimal level of arousal for a given task depends on its complexity and is lower for more complex tasks. Both too much and too little arousal led to diminished performance. Siraji *et al.* further noted that it appeared that the studies showing the most positive effects of light intensity on performance all included conditions of ~1000 lx or more (whether this is horizontal or vertical illuminance is unclear).

In 2019, 18 subject-matter experts convened in Manchester, UK, for the 2nd International Workshop on Circadian and Neurophysiological Photometry, the outcome of which was subsequently published in *PLOS Biology* (Brown *et al.*, 2022). The outcome of their deliberations

was a combined normalized response curve that amalgamated data from both night-time and daytime exposures for melatonin suppression, circadian phase shifting, and self-reported alertness (KSS scores) predicted from melanopic equivalent daylight illuminance; the prediction is for a sigmoidal function. From this function (and as also noted in the chapter on circadian regulation), the workshop participants recommended, for active adults during the day, that the minimum daytime melanopic EDI be 250 lx measured at the eye; then, starting at least 3 hours before bedtime, the exposure should drop to 10 lx; and at night during sleep, it should be not more than 1 lx measured at the eye. A detailed report of the workshop deliberations is available from the CIE (2023).

6.2.2. Well-being

In 2004, a CIE technical report concluded that people in industrialized societies appear to receive too little light exposure each day for optimal well-being (CIE 2004/2009). To date, however, there is no specific recommendation for light exposure in an international standard. All authors agree that to achieve these benefits requires parallel attention to visual comfort and visual performance. Moreover, given the large individual differences in light level preferences (Boyce *et al.*, 2006; Newsham and Veitch, 2001; Viitanen *et al.*, 2013), setting point targets for optimal light levels will be difficult; in addition, context-specific preferences need to be considered (e.g., Wardana *et al.*, 2021).

Laboratory experiments inconsistently find that higher light exposures lead to more positive mood (Leichtfried *et al.*, 2015; Smolders *et al.*, 2012). A meta-analysis that converted light exposures to the CIE S026 quantities found no relationship between mood and light exposure at the eye reported using the five α-opic equivalent daylight illuminances (Nixon *et al.*, 2023).

Advances in technology and in the understanding of ipRGCs have contributed to increased interest in wearable dosimetry, using small devices to record light exposures over time, (e.g., Figueiro *et al.*, 2013; Hubalek *et al.*, 2006; Stampfli *et al.*, 2023). Some such studies using these devices have found that vitality and mood improve with the amount of time spent in an illuminance (usually measured at the wrist) above 1000 lx (generally taken to mean time outdoors, where such levels are more likely to occur) (Smolders *et al.*, 2013). Figueiro *et al.* (2017) found that a high daily light exposure led to more positive mood. Conversely, however, Hubalek, Brink, and Schierz (2010) found no effect of total daily light exposure on mood. aan het Rot, Moskowitz, and Young (2008) took a more granular approach and used ecological momentary assessment to match experiences with the immediately preceding light exposure in a sample of mildly seasonal healthy adults. They found that mood and the quality of social interactions (less quarrelsome, more cooperative) improved immediately following periods of exposure to light above 1000 lx.

6.3. Spectrum

6.3.1. Alertness and Cognition

When it was discovered that the ipRGCs have a different spectral sensitivity than the rods and cones in the retina (Brainard *et al.*, 2001; Thapan *et al.*, 2001) and that the peak lay in the shorter wavelengths (somewhere between 460 and 490 nm), the idea took hold that it might be beneficial for a light source to emit an increased proportion of energy in those wavelengths in order to stimulate the ipRGCs (e.g., Chellappa *et al.*, 2011). Indeed, the CIE technical report 158

(CIE 2004, CIE 2009) included as a principle of healthy lighting the statement that light for biological stimulation ought to include the wavelengths to which the ipRGCs are most sensitive. With legacy light sources, this was accomplished by a change to the mix of phosphors so that more blue-appearing light would be emitted (at the time, the important range was taken to be 460-490 nm). With LED lighting this can be accomplished either using a phosphor coating or by mixing the output of LED chips that differ in colour. Many people assume that such "blue-enriched" lighting necessarily means that the correlated colour temperature of the light source must increase, although this is not true (Esposito and Houser, 2022).

One reason for the strong interest in the effects of light source spectrum on alertness is the potential to increase daytime alertness with lower energy use (Vetter *et al.*, 2022). That is, by manipulating the spectral power distribution (SPD) of a light source to ensure that the ipRGCs are strongly stimulated, the aim is to achieve the equivalent biological effect with a lower energy consumption, as compared to a light source of a different spectral power distribution. In the CIE metrology system, the quantities given by the five *α-opic daylight efficacy ratios* (α-opic DERs) characterise a given light source in comparison to the CIE D65 daylight spectrum (CIE, 2018). A light source with a higher proportion of radiation around 490 nm in its SPD would have a higher melanopic DER.

A large body of research has attempted to demonstrate the value of such "blue enrichmen", or a higher melanopic DER, for acute alertness and cognition, with weak results. A Cochrane review and meta-analysis (a type of systematic review that uses very strict criteria for inclusion) concluded that there is "very low-quality evidence based on two (controlled before-after) studies that high CCT light may improve alertness, but not mood, in daytime workers" (Pachito *et al.*, 2018). Similarly, Souman *et al.* (2018) found that although some studies reported increased self-reported alertness with higher correlated colour temperatures, other studies found no ill effects of filtering out the short wavelengths. Siraji *et al.* (2022) also observed a high degree of variability in the results effects of varying melanopic DER on alertness and cognitive function.

Experimental design and procedural differences have been identified that might explain these variable results (Lok, Smolders, *et al.*, 2018; Pachito *et al.*, 2018; Siraji *et al.*, 2022; Souman *et al.*, 2018; Vetter *et al.*, 2022). Low statistical power associated with inadequate sample size is a common criticism. The presence of other moderator variables, such as time of day (discussed below) and, possibly, participant sex (Chellappa *et al.*, 2017; Hartstein *et al.*, 2018; Huang *et al.*, 2015; Yang and Jeon, 2020) might also explain some of the inconsistency.

Just as the ipRGCs are a relatively recent scientific discovery, it may be that there are other mechanisms yet to be fully elucidated. A few investigations have found that long-wavelength (red) light can increase alertness during both the day and night, in some instances with intensities as low as 40-50 lx (Figueiro *et al.*, 2009; Figueiro and Pedler, 2020; Łaszewska *et al.*, 2018; Plitnick *et al.*, 2010; Sahin and Figueiro, 2013).

6.3.2. Well-being

There is weak evidence for the acute effects of light source spectrum on well-being (Pachito *et al.*, 2018; Schlangen *et al.*, 2014; van Duijnhoven *et al.*, 2019).

For example, two highly cited field experiments that compared a low-CCT fluorescent lamp (2900 K or 4000 K) with a high-CCT lamp (17,000 K) found that the high-CCT lamp was associated with stronger feelings of vitality, concentration, and self-reported work performance (Mills *et al.*, 2007; Viola *et al.*, 2008). Pachito *et al.* (2018) characterized these studies as providing low-quality evidence. By contrast, one experimental report found that participants in a simulated office lit with a high CCT (6000 K) fluorescent lamp reported less positive mood than they did when it was lit with a 2700 K lamp (Smolders and de Kort, 2017). Furthermore, as noted earlier, a meta-analysis of the evidence concerning the effects of light on mood did not find a difference between the effects for the light exposures expressed by the five α-opic EDIs (Nixon *et al.*, 2023), as would have been expected if light source spectrum was the key variable. All of these reviews have noted the limited number of studies that met inclusion criteria and the limited variability in the light sources studied, with few studies carefully manipulating the spectrum to test the influence of specific photoreceptors.

Preferences for light source colour appearance are, arguably, not health outcomes. Nonetheless, they are relevant here as a consideration for selecting a light source spectrum. Several investigations have found that lower CCT values (2700 K – 3000 K) are preferred over higher (~6000 K). These span both laboratory experiments (Guan *et al.*, 2020; Smolders and de Kort, 2017; Viitanen *et al.*, 2013; Yang and Jeon, 2020) and field studies (Akashi and Boyce, 2006; Wei *et al.*, 2014). Previously it had been thought that a relationship (the "Kruithof curve") existed between the correlated colour temperature of a light source and its preferred illuminance, but this idea is now known to be obsolete (Fotios, 2017; Viénot *et al.*, 2009).

The results for colour appearance preferences suggest that a sole focus on maximizing melanopic DER would be unlikely to deliver good lighting quality. Consider that by the same logic, for decades the focus of industry and regulators has been on maximizing visual performance by developing and encouraging light sources with an SPD close to the spectral luminous efficiency function, *V(λ)*, in order to maximize the lumens delivered per watt of input power, a quantity known as the luminous efficacy ratio (LER). An SPD similar to *V(λ)* would have very poor colour rendering (Murphy Jr, 2012), a fact that underlines the need for trade-offs in designing a light source spectrum. As shown in Figure 6.1, an SPD that followed the melanopic spectral sensitivity curve (the sensitivity of the ipRGCs) would also not render colours well because it excludes much of the visible spectrum. Experiments that test various light source spectra using metameric spectral tuning using a multi-channel LED light source might provide an alternative with increased control over the modulation of melanopsin-based photoreceptors without compromising photopic illuminance, chromaticity, and colour rendering (Allen *et al.*, 2018; de Zeeuw *et al.*, 2019; Zandi *et al.*, 2021). This could permit a better balancing of lighting values while adding a dimension (ipRGC stimulation) to the visual considerations discussed by Papamichael, Siminovitch, Veitch and Whitehead (2016).

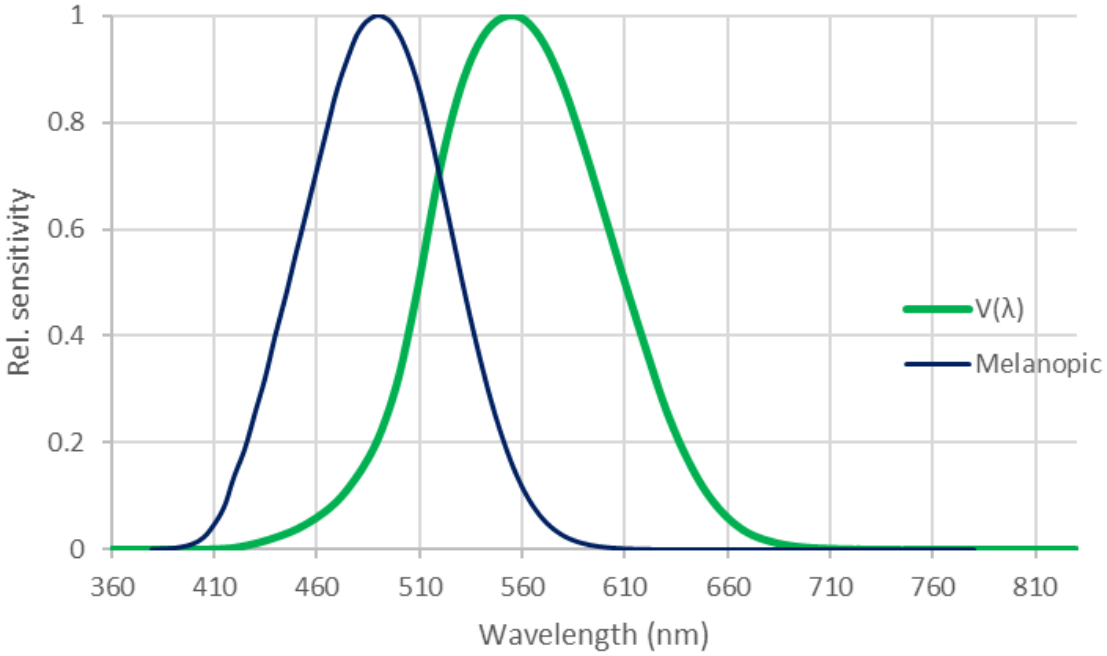

FIGURE 6-1. THE MELANOPIC SPECTRAL SENSITIVITY FUNCTION PEAKS AT 490 NM (CIE, 2018) AND THE SPECTRAL LUMINOUS EFFICIENCY FUNCTION PEAKS AT 555 NM (CIE, 2019).

6.4. Timing

6.4.1. Cognition

It has long been known that the circadian system differs in sensitivity by time of day (Gillette and Tischkau, 1999), which leads to the hypothesis that the acute effects of light exposure ought also to vary depending on the timing of the exposure. There is some evidence for this, although much remains to be known. Investigators seek to identify the dose-response curves for light intensity effects on neuro-behavioural responses at different times of day.

In 2022, an ISO/CIE technical report assessed the claim that lighting "can activate, increase cognitive performance and reduce sleepiness during daytime" as having "insufficient evidence" (ISO/CIE, 2022). For example, studies that have compared morning and afternoon exposures have not identified dose-response relationships in either period (Lok, Woelders, *et al.*, 2018; Smolders *et al.*, 2018); participants in these studies have been well rested people who do not work night shifts.

The ISO/CIE technical report further judged the potential for lighting to achieve these ends during the evening and overnight to have "moderate evidence" (ISO/CIE, 2022). For example, evening light exposure and alertness show a dose-response relationship (Cajochen *et al.*, 2000). The study by Cajochen *et al.* (2000) was necessarily reported using photopic illuminance as the quantity for light exposure (it predated any action spectrum for the ipRGCs), but Hommes and Giménez (2015) included it in their meta-analysis, which found that the response plateaued around 900 lx melanopic EDI.

Xu and Lang (2018) reviewed the literature on light exposure and alertness, including studies of both narrowband and broadband spectra. Their reading of the literature concluded that low

intensity blue light reduces sleepiness during the night, but the effects of blue light were less consistent during the day. In contrast, and consistent with other reviews also published in 2018 (Lok, Smolders, *et al.*, 2018; Souman *et al.*, 2018), white light of moderate intensity seemed effective in reducing daytime sleepiness (Xu and Lang, 2018).

Siraji *et al.* (2022), in their review, divided daytime electric light exposure to morning and afternoon periods and similarly found differences between short-wavelength dominant light and high intensity white light. Short-wavelength-dominant light exposure studies showed more positive effects on cognitive performance in the afternoon; studies of high-intensity white light showed more positive effects in the morning. They suggested that as the homeostatic sleep drive increases across the day, short-wavelength dominant light exposure might become more beneficial for cognitive functioning.

Time of day plays a role in the acute effects of light through circadian processes and through responses to glare, both of which vary greatly between individuals (see the corresponding chapters in this report). These same differences, which are rarely controlled by investigators, could also contribute to conflicting results in studies of acute effects (Gaggioni *et al.*, 2014; Li *et al.*, 2023). Put another way, consideration for individual differences based on their internal timing is important when developing lighting applications (Vetter *et al.*, 2022). Seasonal cycles may also influence the effects of light, where greater illuminance in the morning, but not afternoon, was found to improve alertness but only during the autumn and winter months (Huiberts *et al.*, 2017).

6.4.2. Well-being

Morning light exposure appears to have more consistent results with relation to improving mood compared to afternoon exposure (Xiao *et al.*, 2021; Xu and Lang, 2018). Other studies have found no difference in mood and lighting atmosphere evaluation between morning and afternoon exposure (Kong *et al.*, 2022; Smolders *et al.*, 2012; Zhu *et al.*, 2019). However, from an intensity perspective, bright light has been found to be more comfortable in the morning and afternoon, whereas dim light is more comfortable in the evening (Chen *et al.*, 2021). Such lighting appraisals are themselves important, considering that subjective light evaluation plays a role in well-being outcomes (Veitch *et al.*, 2008; Veitch *et al.*, 2013). Comparing day and night light exposure, a very large cross-sectional study in the UK found that seeking light during the day but avoiding it at night may improve mental health (Burns *et al.*, 2023). More research is needed to characterise the time of the day effect on well-being.

6.5. Duration

The interplay of light intensity, spectrum, and duration is important because these variables will combine to affect the energy required to deliver the right lighting conditions. If a high intensity of light exposure were required all the time, energy regulations would be in conflict with the aim for healthful lighting (Safranek *et al.*, 2020); however, it might be possible to deliver a useful light exposure for a shorter period without undue energy consumption. Another alternative to reduce energy use while increasing light exposure would be to increase the use of daylight indoors.

6.5.1. Cognition

The duration of a given light exposure shows mixed results in relation to cognitive functioning. One review found that exposures varying from 30 minutes to 6 hours at different times of day

did not seem to influence subjective alertness (Xiao *et al.*, 2021). Only two studies included in this review studied conditions of light exposure above 2 h that were also above 1000 lx. Among these two studies, only (Chang *et al.*, 2012) found improvements in alertness, but this was in the context of nighttime exposure. In contrast, the review by Xu and Lang (2018) found that studies with longer exposure durations were more likely to report statistically significant effects. They concluded that an illuminance of at least 1000 lx (unclear, but probably reported for a horizontal surface) for more than 2 hours was required to demonstrate alerting effects. Souman *et al.* (2018) included time of day, time awake, and duration of exposure as potential moderating factors in their review but did not find that these factors influenced alertness. That being said, these authors cautioned drawing any strong conclusions due to missing methodological details, small sample sizes, and a limited number of studies (Souman *et al.*, 2018).

6.5.2. Well-being

There are few investigations into the effects of light exposure duration on well-being measures. A study looking at monochromatic short-wavelength light found that mood improved as duration of exposure increased (Revell *et al.*, 2006). However, monochromatic light sources are not commonly used in everyday interiors. One meta-analysis found that longer durations of polychromatic light exposure, characterised by the five *α-opic* equivalent daylight illuminances, was associated with better mood, but the results did not hold after controlling for the occurrence of subsets of experimental conditions within experiments (Nixon *et al.*, 2023). Duration of light exposure for well-being remains a topic that requires more investigation.

6.6. Light exposure history

Prior light exposure history affects the subsequent responses of the ipRGCs in mammals (Mure *et al.*, 2007) and circadian timing effects of light exposure in humans (Chang *et al.*, 2012). For this reason, light history has been implicated as a potential confounding effect in field and laboratory studies (Peeters *et al.*, 2020; Peeters *et al.*, 2021; Xu and Lang, 2018).

Another way to think about light history is to consider the daily pattern of light exposure. There is a great deal of interest in using the properties of solid-state lighting and controls to deliver patterns of light exposure varying in intensity and spectrum over the day, usually with the intent of mimicking changes in daylight. Such systems are described as providing dynamic lighting, biodynamic lighting, or colour-tuneable lighting, and sometimes (inaccurately) referred to as circadian lighting. Regardless of the label, these systems deliver pre-designed patterns of light (e.g., timed variations in intensity and/or spectrum) across the day, generally with the intent of providing a suitable stimulus for periods of activity or periods intended for relaxation. There have been sufficient such attempts for a systematic review, which concluded that overall mood and alertness did not benefit from daytime dynamic lighting (Kompier *et al.*, 2020). A small number of studies in the review did find an effect for both mood and alertness, although the effects of alertness seem to depend more on time of day (Baek and Min, 2015; Canazei *et al.*, 2014; Hoffmann *et al.*, 2008; van Lieshout-van Dal *et al.*, 2019); there were also differences between the sample populations (e.g., shift workers or not).

One study, which was among those reviewed by Kompier *et al.* (2020), compared laboratory and field study tests of dynamic lighting applications (Aries *et al.*, 2020). They obtained a high degree of discrepancy in results for light appraisal, performance, and affective state between the

laboratory and field setting, which led them to conclude that field studies of specific dynamic lighting applications are necessary before they go into widespread use (Aries *et al.*, 2020). Studies of classroom applications of dynamic lighting, similarly, show gaps requiring further investigation to justify their use (Hansen *et al.*, 2017). This includes expanding the range of outcomes beyond academic achievement and studying the effects of dynamic lighting during winter (especially at higher latitudes), longer-term exposures in the morning of light with more short-wavelength radiation to improve concentration, versus light with more long-wavelength radiation to decrease aggression/increase prosocial behaviour (Hansen *et al.*, 2017).

6.7. Population subgroups

Inter-individual traits and states influence the response to light, which means that there is no one size fits all light source (Boyce, 2022; Gaggioni *et al.*, 2014; Spitschan and Joyce, 2023). The variations are not well understood (Spitschan and Joyce, 2023), but include differences in light sensitivity (Chellappa, 2021), age (Daneault *et al.*, 2014), and chronotype (Refinetti, 2019). It may also be the case that socioeconomic and cultural differences also influence acute (and circadian) responses to light (Li *et al.*, 2023; Spitschan and Joyce, 2023), although there are few investigations that have explored this possibility.

Behaviours also create subgroups, and in particular shift work is an important moderating variable. Working nights has adverse consequences for cognitive functioning, mood, well-being, and health (Boivin *et al.*, 2022; Chellappa, 2020). One way to offset some of these negative effects is through the proper use of light, both to support alertness during the shift and to facilitate circadian regulation and sleep. Reviews have concluded that there is evidence that bright light can be beneficial in reducing sleepiness during the night shift (Aemmi *et al.*, 2020; ISO/CIE, 2022; Lam and Chung, 2021; Vetter *et al.*, 2022; Wu *et al.*, 2022). However, exposure to bright light at night acutely suppresses melatonin, which has adverse consequences for circadian regulation and physiology, both of which contribute to the health problems associated with long-term shift work (Brown *et al.*, 2022; ISO/CIE, 2022; Lunn *et al.*, 2017; Stevens *et al.*, 2014). The development of suitable interventions for night shift work is complex and solutions might require individualization (Vetter *et al.*, 2022).

6.8. Beyond the visible spectrum

The focus of this chapter has been on ocular effects mediated at least in part by the ipRGCs, summarizing what has been learned in the quarter-century since their discovery. Separate lines of research also explore the effects of optical radiation outside the visual spectrum on biology and behaviour, seeking possible beneficial effects (risks are discussed in the chapter on photobiological safety).

Near-infrared radiation (NIR) has been used clinically for many years to reduce pain and speed wound healing (Hamblin, 2016; Hamblin *et al.*, 2018). NIR, usually delivered at a low level directly to the skin, may have cognitive and well-being benefits (Barrett and Gonzalez-Lima, 2013; Blanco *et al.*, 2017; Heiskanen *et al.*, 2020; Meesters *et al.*, 1999; Pan *et al.*, 2023). The dose-response functions and mechanisms of action remain incompletely understood (Carroll, 2019). Nonetheless, the possibility that architectural lighting might benefit from additional NIR has attracted research attention. Giménez *et al.* (2022) added an NIR module to a desk lamp to conduce a double-blind, placebo-controlled trial of varying doses of NIR exposure over four

weeks each in two seasons. In the winter, the added NIR provided benefits for mood, daytime sleepiness, and physiological indices. At present, light sources mostly exclude energy at wavelengths higher than 780 nm because these will reduce the lumens/Watt rating upon which most energy regulations are based. If further research supports these findings, changes to light sources (and to associated regulations) could be required.

At the other end of the spectrum, skin absorption of UV radiation (particularly in the UVB range, 280 – 315 nm) has also been found to have a positive effect on mood and other health outcomes (Slominski *et al.*, 2018; Toledo *et al.*, 2019; Veleva *et al.*, 2018), at least in part through effects on the endocrine system in addition to its effect on pre-vitamin D_3 synthesis (Webb *et al.*, 2022). One possible mechanism is the promotion of serotonin creation by vitamin D; serotonin is a neurotransmitter associated with happiness and well-being (Di Molfetta *et al.*, 2024; Young, 2007). These effects deserve further scrutiny, and not a rush to applications, because the known risks of ultraviolet radiation (UVR) (erythma, skin cancers, ocular damage for people and fading and degradation for materials) must be avoided (Boyce, 2022).

6.9. Conclusions

Every one of the reviews cited here have concluded with remarks about the low quality of the literature. Small sample sizes, short exposures, little or no monitoring or control over prior light exposure, and poorly chosen (and inadequately characterised) stimulus conditions have reduced the evidentiary value of many studies. For example, Nixon *et al.* (2023) observed that it was not possible to differentiate between stimulation of the five photoreceptor types because most investigations varied intensity equally across all five, rather than designing experimental conditions that would specifically target one but not the others. Therefore, they could not test the hypothesis that stimulation of the ipRGCs (in comparison to other photoreceptors) improves mood.

Despite these limitations, the following can be stated:

- The acute neuro-behavioural effects of light occur regardless of the light source. There are no specific positive or negative effects of solid-state lighting as a technology on these outcomes; they depend on the specific characteristics of the light exposure.
- Experimental investigations of light exposure intensity show that self-reported alertness increases with increasing exposure, largely irrespective of the time of day. Physiological markers of alertness and cognitive performance effects are inconsistent.
- Melanopic quantities (melanopic irradiance, melanopic equivalent daylight illuminance) are better predictors of alertness than photopic quantities.
- Ecological monitoring of light exposures (light exposure monitoring that occurs while people go about their daily lives) generally shows that people who experience a higher overall daily light dose report better mood and vitality and possibly better social interactions, but it is not clear from these studies precisely what the optimal dose might be.
- The quantity of the exposure, and not the spectrum itself, determines the acute effect; one can deliver the same quantity using less energy if one tailors the spectrum to increase the melanopic irradiance, while keeping other parameters (e.g., colour appearance, colour rendering) in balance.

- Light exposures during the evening and night have stronger effects on alertness than those during the day.
- It remains unclear whether there is equivalence of exposure for a long duration at a low intensity, or a shorter duration at a higher intensity. This question has importance for practice and lighting energy use.
- There is inadequate information about individual differences in sensitivity to form specific recommendations for subgroups of the population.
- Although initial results are promising, much remains to be learned about the potential uses of long-wavelength radiation, both in the visible range and the NIR region.
- UVR exposure might have some benefits for well-being, but extreme care is needed to balance this against the substantial risks.

6.10. Recommendations

- Increasing daily light exposure is a public health challenge, and governments should treat it as such, communicating to the public that a healthy daily pattern of bright light in the day, low levels in the evening, and darkness during sleep, is required for good health (along with proper nutrition, exercise, and sleep). This is consistent with the official CIE position (CIE, 2024) and the recommendations by Brown *et al.* (2022). Time outside during the day should be part of this message, as this is the most energy-efficient means to deliver a high intensity, even on an overcast day.
- Institutions where individuals are unable to control their light exposure (e.g., hospitals, care homes, schools, workplaces, prisons) should take steps to ensure that every occupant has time every day in bright light; and conversely, that they sleep in the dark. It is an engineering challenge to deliver 250 lx melanopic EDI within current energy regulations (e.g., Safranek *et al.*, 2020), but steps towards a higher light level could nonetheless prove beneficial. Increasing light exposure could be achieved by ensuring time outdoors during daylight hours, or relocation during the day to daylit spaces and near to windows; that is, some progress could be achieved without increased use of electric lighting.
- Further conversation and modelling is needed to identify how to balance building energy regulations with the delivery of higher target light levels, taking into account the increasing efficiency of LED lighting products and controls.
- Building regulations should be altered, where necessary, to ensure that adequate daylight to deliver at least some of the necessary daily light exposure is available in spaces where daytime activities or long-term occupancy occur. As far as we are aware, this is not the case in many countries.
- Governments could consider increasing research funding (possibly by developing multi-national funding pools) to support investigations that will address the research gaps identified here and to support more precise recommendations. A specific area of importance concerns the effect of NIR on health and well-being, because the removal of incandescent lamps from the market has had the unintended consequence of greatly reducing daily exposure to that portion of the spectrum, particularly among people who are unable to spend time outdoors.

7. Long term effects

The cumulated light exposure received during long periods of time, typically several years, has been suspected to play a role in the development of several adverse health conditions. This section summarises the findings of research published since 2012 investigating age-related macular degeneration, myopia in children, and cancer.

7.1. Age-related macular degeneration (AMD)

7.1.1. Background on AMD

Age-related macular degeneration (AMD) is the main cause of blindness among people over 50 years old in developed countries (Modenese and Gobba, 2019). The dry form of AMD (Mitchell *et al.*, 2018) is observed in 80% of patients. It is characterised by the death of photoreceptors and of RPE cells, causing a progressive and irreversible loss of central vision.

There are some similarities between the lesions characterizing AMD and those observed with BLH (Arnault *et al.*, 2013). In both AMD and photochemical retinal damage, the lesions are associated with mitochondrial dysfunction, oxidative stress, and lipofuscin accumulation. In AMD, the RPE is dysfunctional and contains some small deposits of extracellular material called drusen.

These similarities led researchers to test the hypothesis that light exposure could be a risk factor in the development of AMD and could increase its prevalence. Epidemiological studies are now available to investigate the link between AMD and light exposure during very long periods of time. These epidemiological studies may be useful to assess the influence of outdoor light exposure, which is often approximated by the time spent outdoors in specific environments such as an ocean shore, where the sun is the main source of light on the eye.

AMD has many well-known risk factors: age (the most significant), smoking, genetic factors, obesity, hypertension and low dietary intake of antioxidants (Mitchell *et al.*, 2018).

The similarity between light-induced retinal damage and AMD had led several research teams to use animal retinas, such as pig retinas to produce an in vitro model of AMD in order to investigate this condition (Arnault *et al.*, 2013).

7.1.2. Effect of long-term light exposure on the development of AMD

The similarities between the retinal damages characterising AMD and those observed after an acute exposure to blue light (Arnault *et al.*, 2013; Serezhnikova *et al.*, 2017) led researchers to explore the hypothesis of an association between life-long exposure to blue light and the development of AMD later in life.

The environmental exposure to light is the result of direct and indirect daylight components, including the sun, and all the other light sources used in the activities of everyday life. Several epidemiological studies have explored the link between sunlight exposure and AMD, but none of these studies included the light exposure from LEDs in lighting and display devices.

The epidemiological studies investigating the association between sunlight exposure and AMD gave different and conflicting results. Some studies, such as the Beaver Dam Eye study (Cruickshanks *et al.*, 2001) found a significant correlation between sunlight exposure and

development of AMD. During this study, Klein *et al.* (2014) revealed signs of accelerated aging of the retina in the areas which were the most exposed to sunlight.

The European Eye Study (Fletcher *et al.*, 2008) found a significant association between blue light exposure and AMD only for people with a low dietary intake of antioxidants. Other studies did not find a significant link. For instance, no association was found between AMD and estimated lifetime exposure in a French study taking place in Coastal Southern France. However, there was a significant negative association between the use of sunglasses and the formation of soft drusen (Delcourt *et al.*, 2001).

Two meta-analyses were published on the subject and their conclusions are also conflicting. The meta-analysis of Sui *et al.* (2013) found an increased risk for AMD in the populations who received higher sunlight exposures. The meta-analysis of Zhou *et al.* (2018) concluded that sunlight exposure may not be associated with increased risk of AMD based.

The difficulty of reaching a firm conclusion about the role of light exposure in the development of AMD can be attributed to the challenge of accurately estimating the true exposure of the subjects in epidemiological studies (Delcourt *et al.*, 2014). In retrospective studies, recall biases are common among elderly people. Furthermore, individual differences in pupil size and other factors influencing the transmittance of the eye and the retinal exposure, such as the colour of the iris and the yellow pigments of the lens, are difficult to measure.

Despite conflicting epidemiological data on the relationship between sunlight exposure and AMD, the ICNIRP and the SCHEER (SCHEER, 2018; ICNIRP, 2020) stated that high levels of cumulative light exposure may lead to oxidative stress in the retina.

Considering the possible association between long-term light exposure and AMD on the one hand, and by the analogies existing between BLH-related and AMD-related retinal damages on the other hand, several manufacturers of ophthalmic glasses have developed blue light filters for prescription glasses designed to limit the long-term exposure of the retina to the blue light in a narrow spectral range corresponding to the blue light hazard action spectrum (Arnault *et al.*, 2013). The manufacturers put forward better protection of the retina during lifetime, potentially preventing the onset of AMD later in life.

The effective filtering performance of several types of ophthalmic blue light filters were tested by ANSES in France (ANSES, 2010). The weighted transmittance in the spectral range of the blue light hazard (B-lambda curve) was between 85% and 93%. These values are too high to protect the retina against acute exposures responsible for the blue light hazard as defined by the ICNIRP and the photobiological safety standards. Such filters are intended to be used to limit the lifetime environmental exposure to blue light and cannot be used as protective means to limit exposures from high intensity SSL products such as luminaires classified in the Risk Group 2.

7.2. Myopia

7.2.1. Background on myopia

Myopia, or near-sightedness, is the most common visual disorder among young people (Lagrèze and Schaeffel, 2017). The myopic eyeball is excessively long, resulting in images forming in front

of the retina. Distant objects appear blurred while nearby objects can still be sharply seen. Myopia is corrected by wearing prescription glasses fitted with concave lenses or by using concave contact lenses. Myopia usually begins during early childhood and usually progresses until the end of puberty.

The World Health Organisation (WHO) (Mariotti *et al.*, 2015) reported that the prevalence of myopia is increasing globally at an epidemic rate, from 22% of the population in 2000 to 33% in 2020. The WHO also emphasized the alarming proportion of children suffering from the most severe form of myopia, called high myopia, associated with a risk of retinal detachment and other retinal damage referred to as myopic macular degeneration (MMD). These conditions are considered as causes of vision impairment and blindness. The prevalence of high myopia has also increased sharply between 2000 (2.2% of the population of 2000 to 4.0% of the population in 2020).

Several studies demonstrated that the time spent outdoors during childhood was associated with a lower probability of myopia (Rose *et al.*, 2008; He *et al.*, 2015). Conversely, the increase in time spent indoors (Hu *et al.*, 2021; Wang *et al.*, 2021), such as observed during the outbreak of COVID-19, led to an increase of myopia.

Epidemiological studies identified the role of genetic factors and parental history in the onset of myopia (Mariotti *et al.*, 2015). But they make a small contribution in comparison with optical and environmental influences. The time spent outdoors appears to be the most influential factor. Visual tasks performed at near distance in downward gaze play a lesser role. The protective effects of time spent outdoors can offset the negative effects of near work and parental history of myopia. The light exposure received outdoors is the main factor explaining the protective effect against myopia. Other factors in outdoor visual environments were studied such as the spatial frequency content and could be risk factors in the onset of myopia (Brown *et al.*, 2022).

The mechanisms explaining how light influences the development of the eye during childhood have been investigated in several studies (Mariotti *et al.*, 2015). Finding the optimal doses and spectral distributions of light has been investigated to devise prevention means against myopia, including the possible optimization of daylighting and electric lighting in schools (He *et al.*, 2015).

7.2.2. Effect of long-term light exposure on myopia

The exposure to outdoor daylight has been proven to be essential to prevent the onset of myopia in children. Studies have shown that daylight stimulates the production of retinal dopamine which has a regulatory effect on the growth of the eyeball (Norton and Siegwart, 2013). The influences of adenosine and retinoic acid on the elongation have been also demonstrated (Brown *et al.*, 2022).

Several studies carried out on animal models demonstrated the role of blue and violet light exposures in preventing the progression of myopia (Wang *et al.*, 2018; Zou *et al.*, 2018; Najjar *et al.*, 2021; Nickla *et al.*, 2022). Animal studies (Nickla *et al.*, 2022) revealed an influence of the timing of exposure to blue or violet light on ocular growth. In humans (Torii, Kurihara, *et al.*, 2017), myopia progressed less rapidly in a group of myopic children fitted with corrective contact lenses that are transparent to violet light in comparison with a control group fitted with standard glasses filtering up to 50% of the violet light. Torii *et al.* (2017) found a protective effect of violet

light (360 nm – 400 nm) when adults suffering from high myopia received an intraocular implant transmitting violet light, in comparison with a similar group implanted with intraocular implants filtering violet light.

Jiang *et al.* (2021) showed that violet light was the most effective wavelength for myopia suppression in mice. The effect was dependent on both time of day and the retinal expression of neuropsin, an opsin contained in a subclass of retinal ganglion cells discovered in 2003 (Tarttelin *et al.*, 2003). Neuropsin is sensitive to violet light, with a peak sensitivity at around 380 nm. A study found that neuropsin is the only opsin involved in the endogenous retinal circadian clock in the mouse (Buhr *et al.*, 2015), instead of melanopsin or other opsins.

The link between the use of smartphones, tablets and computers by children and myopia was demonstrated in several studies (Enthoven *et al.*, 2020, 2021) and confirmed by a meta-analysis (Foreman *et al.*, 2021) but did not establish a causal link between exposures to LED light and myopia.

7.3. Cancer

7.3.1. Possible mechanisms linking light exposure and cancer

The hormone melatonin occurs in many tissues, but the principal source of circulating melatonin is its secretion by the pineal gland. In vertebrates, melatonin is synthesized at night and circulating levels are low during the day (Aschoff, 1981), regardless of whether the animal is typically active at night or by day. Acute suppression of melatonin by light during a normally dark time has been known for decades, and is the response used both to identify the ipRGCs and to characterise their spectral response (Brainard *et al.*, 2001; Brainard *et al.*, 1988).

Cohen, Lippmann, and Chabner (1978) appear to have been the first to have proposed a link between pineal melatonin and human breast cancer growth. The basis of their hypothesis was the connection between melatonin levels and endocrine function, with disrupted melatonin secretion resulting in excessive oestrogen levels that could promote tumour growth. Environmental lighting (e.g., light exposure at night, suppressing melatonin) was among the sources of melatonin disruption that they listed. Subsequently, researchers tested elements of their hypothesis. For example, Hill and Blask (1988) demonstrated that melatonin could inhibit growth of human breast cancer cells *in vitro* (cells cultured in a Petri dish). Other teams examined similar effects on other cancers, such as melanoma (Hu *et al.*, 1998), and similarly observed that melatonin can suppress cancer growth in cell cultures.

Clearly it would be unethical (as well as impractical) to attempt to directly influence cancer development in humans by any means. An ingenious indirect experiment provided important evidence of the potential systemic effect of light at night on cancer growth (Blask *et al.*, 2005). One team (Blask) performed a xenograft of human breast cancer onto a rat (this is a typical experimental technique in cancer research). A separate team (Brainard) brought women into their lab, and obtained blood samples during the day, at night, or after exposure to light at night. Depending on the intensity of the light exposure and the time of the sample, melatonin levels in the blood samples varied. These blood samples were chilled and sent from one lab to the other overnight. The human blood was then perfused into the xenografted tumours. As predicted, tumour growth was greatest when the blood sample was low in melatonin, as in the case of the

blood samples taken after the exposure to light at night. In addition, melatonin affected the uptake of linoleic acid, suggesting that the active mechanism involves metabolic changes rather than changes in oestrogen availability.

Extensive laboratory research in animals has identified other possible mechanisms by which light exposure at night (or the absence of sufficient light by day) might influence cancer growth. Reduced melatonin levels are one; changes in cancer cell metabolism are another; others include epigenetic changes in the expression of circadian-related genes that are known to contribute to cancer cell proliferation, chronic inflammation, and oxidative damage (Lei *et al.*, 2024). The U.S. National Toxicology Program published an extensive review of this literature (NTP, 2021).

7.3.2. Effect of light exposure in humans

Working night shifts on a regular basis generally means being exposed to light at night and having much-reduced light exposure during the day (when one is sleeping). Epidemiological studies linked long-term night shift work to increased breast cancer risk (e.g., Schernhammer *et al.*, 2001), a body of research that led the International Agency for Research on Cancer to declare in 2007 night shift work a class 2A carcinogen (IARC, 2010), a decision reiterated in 2020 (IARC, 2020). The IARC conclusion is that "Night shift work is probably carcinogenic to humans," noting limited evidence in humans but sufficient evidence in animal experiments. The U.S. National Toxicology Program similarly concluded that "There is high confidence for a causal relationship between human cancer and persistent night shift work — i.e., frequent and long-term night shift work, especially beginning in early adulthood—that causes circadian disruption" (NTP, 2021, p. 222). It is important to note, however, that night shift work is not synonymous with light exposure. Night shift workers may also have a poor diet (e.g., opportunities to eat nutritious meals are often fewer overnight), sleep less (particularly if trying to maintain family and social relationships), exercise less, and in some instances may be exposed to other occupational hazards.

When considering how light exposure might influence cancer risk, both sides of the equation deserve consideration. As early as 2004 the CIE concluded that a fundamental principle of healthy lighting is the maintenance of a daily pattern of light and dark (CIE, 2004/2009). The same report also noted that the available exposure data shows that the daily light exposure of urban-dwelling adults is low, a fact that has been repeated in several studies since then (e.g., Daugaard *et al.*, 2019; Smolders *et al.*, 2013). Animal experiments have shown that increasing the daytime light exposure increases the amplitude of the night-time melatonin secretion (Dauchy *et al.*, 2016) and this, in turn, inhibits cancer cell growth (Dauchy *et al.*, 2015). There is growing interest in naturalistic light exposure monitoring and new instruments being developed (e.g., Stampfli *et al.*, 2023), which should improve the quality of research and will contribute to filling gaps in knowledge in this field.

Exposure to light at night, however, is ubiquitous in the urban settings where most humans live and difficult to avoid even in rural settings (see Figure 7.1). The U.S. National Toxicology Program concluded that there is "moderate confidence for a causal relationship between human cancer and certain lighting conditions — i.e., excessive [light at night] LAN exposure combined with insufficient daylight exposure — that cause circadian disruption" (NTP, 2021). Their conclusion was based on the evidence that exposure to light at night, regardless of the light source, influences mechanisms that are known to be likely to cause cancer. Although the evidence points

to the intensity, timing, and spectrum of the light exposures as being the influential parameters, they were unable to specify the exact conditions that most increased the risk (nor the best conditions to reduce the risk).

FIGURE 7-1. AN IMAGE OF WESTERN EUROPE AT NIGHT TAKEN FROM SPACE (MARCH 2012)

7.4. Conclusions

7.4.1. Conclusions on age-related macular degeneration (AMD)

The mechanisms of retinal ageing were studied in vivo and in vitro. These studies point out the primordial role of oxidative stress triggered by chronic light exposures in the retina.

The role of long-term light exposure 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.

More research is needed to study the link between long-term exposure to light emitted by SSL products and the development of AMD.

7.4.2. Conclusions about 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, with several aspects in it: the amount of daily light exposure, the timing of this exposure during the day and the spectral distribution of light.

The shortest wavelengths of the visible spectrum up to 400 nm, namely violet light, 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. The protective influence of violet light was proven in animal studies and in one study carried out on children. More research is needed to understand the interplay between the different photoreceptors and photosensitive retinal ganglion cells.

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.

Solid-state lighting products are based on LEDs which do not emit violet light, apart from violet-pump phosphor-converted white LEDs which are used in a very small fraction of lamps and luminaires. No study has investigated the use of such LEDs to prevent myopia or slow its progression.

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.

7.4.3. Conclusions about the link between SSL products and cancer

The scientific consensus is that cancer risk increases when the individual lacks a strong daily light-dark rhythm. That is, the conditions to avoid are both too little light exposure by day and too much light exposure at night. The precise mechanisms underlying the increased cancer risk are not fully understood yet, nor is it possible to specify the intensity, duration, timing or spectrum limits to reduce the risk (Zielinska-Dabkowska *et al.*, 2023). There is no evidence of which we are aware to suggest that any specific lighting product or system is implicated in the light exposure-cancer relationship.

7.5. Recommendations

7.5.1. Recommendation on age-related macular degeneration (AMD)

Well-designed general lighting systems should not be considered as a risk factor in the development of AMD. However, repeated exposures to high levels of light emitted by high

intensity SSL products used in specific applications (stage lighting, stadium illumination, etc.) should be avoided to protect the retina against photochemical damage as it is known to be cumulative over the lifetime.

7.5.2. Recommendations about myopia

As general lighting products are not currently designed to deliver an amount of light and a spectral distribution comparable to daylight, general SSL products should not be considered useful to protect children against myopia.

Using violet-pumped phosphor-converted white LEDs in SSL products to enhance the exposure to violet light indoors should be considered with caution. The retinal phototoxicity of LEDs based on this technology was tested on rats and revealed a lower damage threshold than with blue light (Jaadane *et al.*, 2020).

The role of violet light in regulating the growth of the eyeball should be the subject of further research. The role of the newly discovered neuropsin, an opsin found in a subclass of retinal ganglion cells and sensitive to violet light, should be investigated with the objective to determine an action spectrum and establish dose-effect relationships. The set of alpha-opic action spectra defined by the CIE (2018) might need to be expanded to include neuropsin-related quantities.

7.5.3. Recommendations about the link between SSL products and cancer

The fact that cancer risk is associated with the daily rhythm of light and dark means that there are both individual responsibilities and regulatory responsibilities in reducing risk.

For independent-living adults, ensuring a strong daily light-dark rhythm means taking steps to (1) increase light exposure during the active part of the day, ideally by spending time in daylight because it is orders of magnitude higher than any electric lighting system in an interior; and (2) reduce light exposure at night while sleeping. This can be achieved using blackout blinds or curtains to exclude any light from outdoors, or by wearing a sleep mask. Relevant authorities will need to take care to provide appropriate light and dark exposures for children and those whose activities are restricted for any reason.

The energy-efficiency of SSL sources brings with it a temptation to increase the amount of exterior light – including through the use of large electronic signs and displays – which should be resisted. Regulatory bodies could reconsider the use of exterior light at night, especially in residential areas where it could adversely affect humans. With advanced controls, it could be possible both to increase energy savings by dimming or turning off street and display lights overnight (e.g., by setting a curfew) while also reducing the risk of cancer and other adverse health effects. Improved luminaire designs that reduce stray light and place useful light where it is needed (e.g., on pedestrian routes and not into homes), would also benefit both the environment and human health.

8. GENERAL CONCLUSIONS

The conclusions concerning each effect category are summarised in the following sections.

8.1. Photobiological safety

The effects of blue light on the retina during a short-term acute exposure is known as the blue-light hazard. Although some studies have suggested that the blue-light hazard may happen below the currently known threshold, there is currently no consensus about the need to revise the exposure limits to the blue light hazard.

Known sensitive populations to the blue light hazard are children, aphakic and pseudophakic subjects (respectively defined as people having no crystalline lens or wearing an artificial lens implant), elderly people and people suffering from preexisting ocular pathologies. These sensitive populations are not considered by the current photobiological safety standards used to classify lamps and luminaires in different risk groups.

Measurement campaigns showed that domestic and office lighting SSL products are classified in Risk Group 0 (no risk) or in Risk Group 1 (low risk) for the blue-light hazard, like older lighting technologies. Street lighting, sport lighting, industrial lighting and other professional SSL products may belong to Risk Group 2 (moderate risk). No measurement data were found in these product categories.

The blue light hazard may be more critical at night, rather than during the day. However, no quantitative information is available to define photobiological safety thresholds as a function of the circadian clock.

The protective effects of red and near-infrared radiation have been studied but it is not possible yet to conclude that there is a beneficial effect against the blue-light hazard or other retinal hazards.

8.2. Discomfort Glare

Unwanted light (areas of extreme intensity or very high contrast in or slightly outside the field of view) can cause visual discomfort. Predictive models exist, but these were developed for legacy light sources with large uniform emitting areas.

There is limited information about individual differences. Age is poorly understood. It is currently not included in normative evaluations. Younger people have been found to be more sensitive to discomfort glare and quickly bothered by it. Older people may be less sensitive to discomfort glare but may experience a decrease in their visual performance after a prolonged exposure to discomfort glare.

Discomfort glare can trigger and aggravate headaches in people suffering from migraines. The mechanisms linking strong light levels and headaches revealed a contribution of visual pathways, with a possible influence of the spectral distribution of light. A possible physiological basis for photosensitivity involving pain receptors and pain-modulating mechanisms may explain the aversive or painful responses to glare in sensitive people.

Discomfort glare experienced when performing work-related visual tasks over long durations is a factor contributing to eyestrain, irrespective of the lighting technology. Eye-tracking measurements have revealed the altered behaviour of the eyes during an exposure to a glare source.

Discomfort glare has been found to change according to the circadian clock, decreasing as the day progresses. The mechanisms explaining this circadian change of sensitivity to discomfort glare are not known.

As far as SSL products are concerned, large area uniform sources are intrinsically associated with less discomfort glare than small size sources. The non-uniformity of SSL lamps and luminaires is detrimental to discomfort glare. The correct assessment of discomfort glare indoors can be done using a correction factor applicable to the UGR (R_{UG}). Discomfort glare experienced outdoors at night from non-uniform sources has not been extensively studied.

The spectral power distribution of light has an influence on discomfort glare. LEDs emitting a high proportion of short wavelength (blue) light cause more discomfort glare than other types of white light. White LED light with lower CCT values (warm white) are perceived as less glary than with high CCTs (cool white). Several mathematical models are available in the published literature to describe the spectral dependency in the assessment of discomfort glare, but there is currently no consensus about these models.

8.3. Temporal light modulation

Temporal light modulation (TLM) is a property of light sources and lighting systems, which can vary in luminous or chromatic output over time. There is ample evidence that TLM affects human physiology and behaviour, with implications for health and well-being. TLM is detected at the eye. Modulated signals reaching the brain are noise, not contributing information to the visual image. Processing this noise takes cognitive resources, increasing brain activity and blood flow. The noise includes competing information that disrupts saccades, interfering with visual performance. The noise can include visual perceptions such as flicker, stroboscopic effects, and the phantom array effect. The increased cognitive load, together with the disrupted eye movements, affects cognitive performance. The increased effort required can manifest in eyestrain, headache, and fatigue, particularly over longer periods.

It is no longer a question of whether TLM affects observers, but of what range of conditions ought to be permitted. Expert stakeholders had hoped that a single quantity might predict many outcomes, but that now seems unlikely, given the emerging data for the phantom array effect as compared to the stroboscopic effect.

Pulse-width modulation (PWM) is the most common form of dimming for LED products, and often introduces rectangular wave TLM to the light output. Rectangular waveforms show consistently the most problematic outcomes for observers. Even in the limited jurisdictions that regulate TLM, the regulations do not apply to the performance of products in a dimmed state.

Sensitive individuals might react sooner and/or more intensely, or experience more serious consequences such as migraine and photosensitive epileptic seizures.

8.4. Circadian effects

Many physiological processes show daily rhythms known as circadian rhythms, which are synchronized primarily by a regular daily pattern of light and dark exposure. Depending on its timing, amount and wavelength, light exposure that is not part of this regular daily pattern 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 (meaning that processes that should occur overnight occur later), while light exposure in the morning advances the circadian clock (meaning that some processes occur earlier than they otherwise would). 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 moderated by daytime light exposure, making the relationship between light exposure and sleep somewhat complex. Effects of light on metabolic functions are less clear, and more research is needed before any conclusions can be drawn. It is important to note that this conclusion largely pertains to healthy, day-active young and working-age adults. The need for a daily pattern of light and dark exposure for all is well established, but there is more to learn about how light exposure affects sensitive populations, such as children, the elderly, or shift workers.

Exposure assessment is extremely important in evaluating the potential circadian effects of light. The melanopic EDI (Equivalent Daylight Illuminance) provides an exposure index that can be used for this purpose.

8.5. Acute neuro-behavioural effects

Light exposure can have immediate effects on physiology and behaviour; these are called “acute effects”. The effective exposure determines the acute effect. The effective exposure is a function of the quantity of light, the spectrum, and the spectral sensitivity of the photoreceptors involved.

Experimental investigations of light exposure have shown that self-reported alertness increases with increasing exposure. Light exposures during the evening and night have stronger effects on alertness than those during the day. Melanopic quantities, such as the melanopic EDI, are better predictors of alertness than photopic quantities. One can deliver the same quantity using less energy if one tailors the spectrum to increase the melanopic irradiance, while keeping other parameters in balance. However, it is not possible to conclude that the stimulation of the ipRGCs, in comparison with the other photoreceptors, improves mood or alertness. The data for physiological markers of alertness and cognitive performance effects remain inconsistent.

People who experience a higher overall daily light exposure report better mood and vitality and possibly better social interactions, but it is not clear what the optimal exposure might be. It remains unclear whether there is equivalence of exposure for a long duration at a low intensity, or a shorter duration at a higher intensity. This question has importance for practice and lighting energy use.

Although initial results are promising, much remains to be learned about the potential uses of long-wavelength radiation, both in the visible range and the near infrared region. UV exposure might have some benefits for well-being too, but extreme care is needed to balance this against the substantial risks.

8.6. Long-term effects of exposures to SSL products

8.6.1. Age-related macular degeneration

Several studies have revealed phototoxic effects of low doses of blue light on the retina during long-term chronic exposures. These studies point out the primordial role of cumulative oxidative stress of the retina triggered by chronic light exposures.

The role of long-term light exposure on the development of age-related macular degeneration (AMD) remains controversial. It has not been firmly established by all the available epidemiological studies, and meta-analyses of these studies have reached conflicting conclusions. In the published epidemiological studies investigating AMD, the contribution of the exposure to electric light in the overall light exposure could not be assessed. Therefore, it is impossible to conclude anything about the effect of long-term chronic exposures to SSL products on the development of AMD.

8.6.2. 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, with several aspects in it: the amount of daily light exposure, the timing of this exposure during the day and the spectral distribution of the light.

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, is indirectly correlated with myopia through the reduction of time spent outdoors, as these objects have been increasingly popular among children.

The shortest wavelengths of the visible spectrum down to about 400 nm, namely violet light, 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, an opsin contained in a class of ipRGCs sensitive to violet wavelengths. Solid-state lighting products are based on LEDs which do not emit violet light, apart from violet-pump phosphor-converted white LEDs which are used in a very small fraction of lamps and luminaires. No study has investigated the use of such LEDs to prevent myopia or slow its progression.

Existing general lighting systems cannot provide light exposures comparable to the outdoors in terms of quantity and spectral content. Unlike daylight, the light emitted by current SSL lighting systems has very little components near the lower and upper limits of the visible spectrum (near-infrared, red, violet, and ultraviolet wavelengths).

8.6.3. Cancer

The scientific consensus is that cancer risk increases when the individual lacks a strong daily light-dark rhythm. That is, the conditions to avoid are both too little light exposure by day and too much light exposure at night. Several possible mechanisms have been proposed for the increase in cancer risk, and these may differ between cancer subtypes. Among the proposed mechanisms are reduced melatonin secretion, disrupted circadian rhythms, chronic

inflammation, and epigenetic changes in the action of various genes (especially those involved in circadian regulation).
The lack of a strong daily rhythm of light and dark can occur among day-active people who spend most of their time indoors without much access to daylight, or whose sleeping environments are not dark. People who work long-term night shifts are a special population, and this working schedule has been identified as a cancer risk factor in itself. It is unclear that light exposure and/or circadian rhythm disruption alone are the causal factors in the cancer risk for night shift workers because several other variables also co-occur for night shifts (e.g., limited access to healthy meals; workplace health risks; social isolation; family-related stressors).

There is no evidence to link any specific light source to cancer risk. The long-term effective dose depends on the intensity of the light, its spectral power distribution, and the spectral sensitivity of the photoreceptors involved, as well as the timing and duration of the light exposures. If melatonin secretion is among the mechanisms, then the ipRGCs are implicated, but it remains unclear whether other photoreceptors might also contribute.

9. Recommendations

9.1. Application recommendations about sensitive populations

9.1.1. Photobiological safety (PBS)

The PBS risk groups of SSL products intended to be used by sensitive populations, including children and adolescents, elderly people, and people having a retinal disease, should be assessed using lower exposure limits. In addition, the blue light radiance weighted exposure should be assessed using the aphakic action spectrum defined by ICNIRP.

Because retinal sensitivity increases at night, places in which night work happens, and places where people are exposed at night, should be lit with SSL products classified in a lower risk group than places in which there are only daytime activities.

9.1.2. Discomfort glare

As some SSL products may produce high luminance levels or high luminance contrasts with their environments, they should be used with care in the presence of people suffering from migraines and people generally averse to strong lights. The direct viewing of high-power SSL luminaires is not recommended, especially for sensitive populations. Luminaires with a high proportion of short-wavelength light (e.g., those marketed as 'cool white') should be used with care in the presence of sensitive people to discomfort glare.

9.1.3. Circadian effects

Some populations may require specific lighting conditions to optimize their circadian rhythms and sleep. For instance, 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 from healthy adults working daytime hours, and more research is needed to determine their optimal lighting conditions.

9.1.4. Temporal Light Modulation

Temporal light modulation (TLM) affects everyone. Some people are affected more than others, but there remains disagreement about the proportion of the population that experiences severe problems. There are diagnostic tests to identify the individuals most likely to experience visual disturbance and headaches in response to TLM, but these individuals have no way to identify whether a given location might expose them to conditions that trigger their adverse effects. By taking steps to reduce the TLM of the light sources or lighting systems, the risk to any individual of unintentional exposure to an adverse condition can be eliminated.

9.2. Research priorities

The risk group classification of CIE S009:2002/IEC 62471:2006 is based on the blue light hazard weighting function for the general population. Yet, the sensitivity of children and other sensitive populations is best described by the aphakic retinal hazard spectral weighting function, recommended by ICNIRP for children under 2-year-old. The two sensitivity curves greatly differ below 430 nm. For instance, at 400 nm, the aphakic weighting function is 14 times higher than the blue light hazard weighting function. At 380 nm, it is 319 times higher. For this reason, more data is needed concerning the emission levels of SSL technologies at wavelengths below 430 nm.

Knowing these emission levels would enable to assess the photobiological safety for sensitive populations in a more reliable way, and measure how the results differ from the standard assessment based on the sensitivity of the general population.

Particular products that might have high emissions in this spectral range could include lamps and luminaires using violet-pumped phosphor-converted white LEDs. Other examples are SSL lamps and luminaires incorporating blue or violet LEDs used to “enrich” the emitted white light for various purposes such as colour-tuneability or circadian stimulation.

More data concerning high-power SSL products used in professional applications such as street lighting, sport lighting and industrial lighting, are needed. According to the current product safety standards, these products may belong to Risk Group 2. In this case, they should bear a safety mark and an indication of the safe viewing level, expressed in terms of a threshold illuminance or a threshold distance. It is recommended to assess if these indications are compatible with the intended applications.

More research is needed to study the effects of enriching the spectral distribution of SSL products using combinations of red or near-infrared with violet and ultraviolet wavelengths for applications such as alleviating the blue light hazard, reducing the risk of AMD development, improving mood and cognition, or limiting the onset of myopia in children. Adding any narrow band light in general lighting to target a single mechanism is potentially problematic as it is likely to produce other unexpected outcomes. Increasing the dose of light delivered to the eye should be investigated considering the balance between benefits and risks involving all the aspects of the light exposure.

Lighting researchers and neuroscientists should carry out more multidisciplinary research to better understand the mechanisms underlying visual discomfort and explore the relationships between environmental stimuli (including contextual variables that moderate discomfort from lighting conditions) and neural responses. The use of eye-tracking techniques and other physiological measurements is encouraged when feasible. Studies could address discomfort glare experienced with non-uniform SSL street and road lighting luminaires in situations of proximity between the subject and the luminaire. Although the influence of the spectral distribution of light on discomfort glare has been demonstrated, further studies should be undertaken to reach a consensus among researchers. The consequence of glare on visual performance in children and other sensitive populations, such as people having eye diseases, should be studied in more details.

More research is recommended to further explore the findings concerning the circadian variations of discomfort glare observed in the reviewed studies. It would be useful to investigate whether the observed circadian variation in discomfort glare could be driven by the excitation of the ipRGCs known to be involved in the regulation of the central biological clock and in the pupil constriction reflex. With additional information it would also be possible to evaluate the potential for conflict between increased glare sensitivity and the need for a high light exposure at the same time.

The general recommendation for healthy light exposure patterns is “bright days, dark nights”. The only consensus document with criteria for the target exposures in day, evening, and night-time (which is based primarily on data from healthy young or middle-aged adults) does not

address questions of exposure duration (Brown *et al.* 2022). For example, the daytime recommendation is for a minimum exposure of 250 lx melanopic EDI measured vertically in the direction of gaze. If electric lighting is the only light source, this is a difficult target to achieve within current energy regulations in most jurisdictions, even with SSL, and it might also conflict with other lighting design goals. Further research is needed to determine whether a shorter duration of exposure at this level might be acceptable. Furthermore, is there an equivalency between shorter exposures at a higher level, and longer exposures at a lower level? What are the consequences of light exposure patterns in some combination of exposures of varying levels at varying durations? Similarly, how serious are short night-time exposures to a higher light level than the maximum 1 lx melanopic EDI? These effects are of interest both for immediate effects on sleep, cognitive function, and well-being, for circadian regulation, and for long-term consequences. More research is also needed to understand the interplay between the different photoreceptors and photosensitive retinal ganglion cells.

Research on the effects of light exposure on infants' and children's sleep remains sparse, and given the importance of sleep for development, this constitutes an important future research need. Likewise, more research specifying clear lighting intervention guidelines for older adults and shift workers is needed to provide optimal lighting environments to improve their sleep and strengthen circadian rhythms.

As regards temporal light modulation, it is clear that no single derived quantity will predict all behavioural outcomes. Currently, knowledge of various outcomes is application-specific, but it might be possible to develop generally applicable new indices and limit values. For example, the phantom array effect is best understood in automotive lighting but less well understood in interior lighting. Researchers could develop predictors of the phantom array from which limit values could be set that would apply to various applications. There is a particular gap with respect to TLM predictors to reduce the risk of headache and task performance decrements. This area of research would be most efficient if it focused on sensitive populations to increase statistical power and to determine what range of conditions ought to be permitted.

In all areas detailed above, strong research designs are needed to ensure the validity and reliability of behavioural measures in order to determine the range of conditions that best supports the population. Researchers should also ensure that investigations include diverse populations within the bounds of the research question, and this also includes replications in various cultures and communities.

9.3. Recommendations for SSL product manufacturers

In order to ensure that products are low risk for the blue light hazard, narrow band short wavelength light (blue and violet) should not be used alone in general lighting products.

Glare and temporal light artefacts, such as flicker and the stroboscopic effect, can be experienced almost instantaneously by people, resulting in immediate negative outcomes. In designing SSL products, manufacturers should target their efforts at reducing these effects.

Manufacturers should assess the discomfort glare of their products in the intended application configurations. Non-uniform SSL products for indoor lighting should be assessed using the

corrected UGR defined by the CIE. SSL lamps intended to be used at short viewing distance (especially for home use) should be shaded or diffused to lower the risks of discomfort glare.

SSL systems could be designed to reduce or to eliminate the potential of TLM, for instance by avoiding the focus on PWM dimming and its rectangular waveforms. Combinations of constant current reduction, pulse frequency modulation and pulse width modulation dimming could be used. Manufacturers could consider reporting TLM values on their technical datasheet to inform users, particularly in jurisdictions where it is not required.

General lighting products are not intended to be used under medical supervision. For this reason, they should be designed to be intrinsically safe, without relying on assumptions that would be too restrictive on users' behaviour, such as "the viewer has no reason to stare at the light source", or "the aversive response is fast enough to avoid damage to the retina". These assumptions may not always hold for specific populations, such as children, visually impaired people, people suffering from mental illnesses, etc.

9.4. Recommendations for standardisation bodies

Standardisation bodies have important roles to provide the link between science and regulation. Expert committees proposing to establish guidance on matters related to light and health should include the appropriate diversity of scientific and applications expertise so that scientifically sound yet practical guidance documents result, preferably with a degree of co-ordination to avoid conflicting guidance.

9.4.1. Recommendations for photobiological safety standardisation committees

Following the conclusions of several independent studies of retinal phototoxicity using modern detection techniques, we recommend that photobiological safety committees engage in a systematic review and update of the blue light hazard exposure limits. Before this process reaches its conclusions, we do not recommend assessing the photobiological safety of SSL products using more permissive applications standards.

9.4.2. Recommendations for lighting standards

Lighting standards recognize glare as a major cause of visual discomfort. In the future, lighting standards should include more accurate ways to predict discomfort glare by considering the spectral distribution of light and the non-uniformity of outdoor luminaires seen at close distances, in pedestrian lighting for instance. In addition to specifying maintained illuminances to fulfil visual comfort and performance needs, lighting standards could include maximum light levels at the eye in places used at night to limit glare.

Following the development of improved information about TLM effects on targeted outcomes and the development of validated derived quantities to predict these effects, standards with limit values for TLM should be developed. In the nearer term, these standards could reduce reliance on technologies that produce rectangular waveforms. Regulators could consider referencing these standards to make their application mandatory, as a matter of protecting vulnerable people.

Lighting standards could explore the interactions of lighting design with technology and controls, enabling the delivery of a higher light exposure by day without unduly increasing energy use for lighting.

9.5. Recommendations for regulatory bodies

9.5.1. Recommendation on SSL product regulations

The recently published standard IEC 62471-7 defining photobiological safety compliance requirements for lighting products based on their intended application, should be used with caution as it is more permissive than the current regulations based on the risk group classification defined by the CIE S009:2002/IEC 62471:2006 standard and the North American ANSI/IES RP-27-20.

Regulations are required to further tighten the potential for TLM, especially in products that are dimmed. It is recommended to extend criteria in standards and regulations to cover the entire dimming range of lamps and luminaires.

The use of the correlated colour temperature (CCT) to describe light source spectrum is not appropriate for health recommendations because a vast number of spectra can achieve the same CCT. Health recommendations should be based on quantities that are specifically defined for this purpose, such as the quantities defined in CIE S026 for ipRGC-influenced effects.

9.5.2. Recommendations for public health authorities

Places where long-term exposures can be foreseen, such as schools and offices, should not be lighted with luminaires whose compliance with photobiological safety and temporal light modulation requirements has not been reliably proven. Discomfort glare from lighting installations should be carefully assessed in these premises.

Given that it is well established that a healthy pattern of light and dark every day is necessary for good health, all lighting recommendations should reflect the need to deliver this pattern. Doing so in an energy-efficient manner might involve using a higher proportion of shorter-wavelength light during the day to increase the effective exposure with less energy and emphasizing longer wavelengths at a lower intensity in the evening to maintain a lower exposure. The choice of light source spectrum and intensity, however, must balance other lighting goals; lighting recommendations that integrate the various purposes of a lighting installation are to be preferred over documents that target only circadian regulation, or visual performance, etc. For the time being, until further information accrues, the target maintained daytime illuminance could be set at 250 lx melanopic EDI or higher at the eye; for evening, a maximum of 10 lx melanopic EDI at the eye or less; during sleep, 1 lx melanopic EDI at the eye or less.

Most people spend time in a variety of places over the day, and therefore achieving the healthful pattern of light and dark is often a matter of personal responsibility. Therefore, public health agencies and departments alongside energy and industry regulators should work together to promulgate information about the best way to use light to benefit health. This is a problem of communication as well as possibly of regulation.

For individuals who are active during the day, daylight remains the best source of light exposure since it is available at the right times, with a quantity and a quality adapted to human needs. Electric lighting cannot replace it entirely, as the amount of light delivered at the eye is insufficient, the spectral distribution can be unbalanced, and the timing of the exposures is not always in phase with the biological clock. In schools, making daylight time a required part of every daycare and school day is recommended to prevent myopia, especially for children under eight years old. Unfortunately, some populations cannot access daylight. In their cases, measures should be taken to make their daily light exposure higher and their nights darker. Nursing homes, long-term care facilities, and prisons should implement such measures to help maintain the individual and collective quality of life in their premises.

10. Closing Remarks

The number and diversity of scientists studying the effects of light on physiology, behaviour, and health continues to increase and the number of publications in these subfields continues to show an exponential increase. Interest in this topic among the entire lighting community continues to be high. Although not the primary purpose of this report, this synthesis of the state of knowledge provides some guidance to researchers.

This report fills a gap in the lighting world with its focus on SSL products and on aspects that might be worthy of regulation. The overall aim, consistent with the goals of the SSL Annex and its successor the Smart Sustainable Lighting and Controls Platform, is to ensure an orderly transition from legacy lighting systems to SSL systems with their associated energy savings and environmental benefits – and, we hope, product characteristics that benefit human health as well.

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