ICNIRP Statement

ICNIRP Statement on Short Wavelength Light Exposure from Indoor Artificial Sources and Human Health

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Abstract—**Concerns have been raised about the possibility of effects from exposure to short wavelength light (SWL), defined here as 380–550 nm, on human health. The spectral sensitivity of the human circadian timing system peaks at around 480 nm, much shorter than the peak sensitivity of daytime vision (i.e., 555 nm). Some experimental studies have demonstrated effects on the circadian timing system and on sleep from SWL exposure, especially when SWL exposure occurs in the evening or at night. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has identified a lack of consensus among public health officials regarding whether SWL from artificial sources disrupts circadian rhythm, and if so, whether SWL-disrupted circadian rhythm is associated with adverse health outcomes. Systematic reviews of studies designed to examine the effects of SWL on sleep and human health have shown conflicting results. There are many variables that can affect the outcome of these experimental studies. One of the main problems in earlier studies was the use of photometric quantities as a surrogate for SWL exposure. Additionally, the measurement of ambient light may not be an accurate measure of the amount of light impinging on the intrinsically photosensitive retinal ganglion cells, which are now known to play a major role in the human circadian timing system. Furthermore, epidemiological studies of long-term effects of chronic SWL exposure per se on human health are lacking. ICNIRP recommends that an analysis of data gaps be performed to delineate the types of studies needed, the parameters that should be addressed, and the methodology that should be applied in future studies so that a decision about the need for exposure guidelines can be made. In the meantime, ICNIRP supports some recommendations for how the quality of future studies might be improved.**

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INTRODUCTION

This statement summarizes the current scientific evidence on the effects of exposure to short wavelength light (SWL), defined here as 380–550 nm, from artificial sources on human health, focusing on the disruption of circadian rhythms. It does not address the acute damaging effects on the human retina known as the "blue light hazard," or indirect effects on health (e.g., via ecosystem disruption).

Over the past few decades, the likelihood that humans are exposed to higher amounts of SWL has increased, especially at night (ANSES 2019). This is due to changes in lighting technology (ACGIH 2022; ANSES 2010) and consumer behavior (Cajochen 2011). Traditional incandescent lamps tended to be more yellow-orange in hue (with a large proportion of their emissions in the 560–630 nm range)

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compared to fluorescent and light-emitting diode (LED) lamps, which emit proportionally more SWL (ibid). The popularity of smartphones, laptops and tablets have contributed to the increased availability of artificial light at all times, including in the evening. Smartphones, laptops and tablets typically contain LEDs, which emit more (absolute) SWL than other light sources (ibid).

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) published guidelines in 2013 for exposure to incoherent visible and infrared radiation (ICNIRP 2013). This publication provided exposure limits to protect the human retina from potential phototoxic effects of SWL (i.e., the "blue light hazard"). Effects of SWL on circadian rhythm were not considered at that time. In 2020, ICNIRP published a statement that analyzed the potential hazards from exposure to LEDs (ICNIRP 2020). The conclusion of these publications was that exposure to LEDs and other artificial lighting sources does not pose an optical radiation hazard to the general population under typical use conditions. The ICNIRP LED 2020 statement (ibid) only briefly mentioned the effects of blue light (part of the SWL spectral range) on circadian rhythm disruption.

Concerns have been raised about the possibility of effects of SWL on the human circadian timing system and its impact on sleep, especially when SWL exposure occurs in the evening or at night (AMA 2012; ANSES 2019; Cajochen et al. 2005, 2011; Fisk et al. 2018).

ICNIRP has identified a lack of consensus among public health officials regarding both whether SWL from artificial sources disrupts circadian rhythm and whether disrupted circadian rhythm is associated with adverse health outcomes.

Therefore, the main aims of this Statement were:

- To provide a critical overview of the evidence for impacts on human physiology (including effects on the circadian timing system, the neuroendocrine system and sleep); and
- To assess whether there is sufficient evidence to determine whether there are adverse health effects from exposure to SWL from artificial light sources.

In addition, the Statement covers:

- Evidence for increasing use of SWL sources;
- Emission characteristics of newer compared to traditional light sources;
- Known biological mechanisms associated with exposure to SWL;
- Review of limitations in current research; and
- Recommendations for future research including improvement of dosimetry to adequately assess potential adverse effects of SWL.

The spatial and temporal characteristics of SWL sources are not related to their radiation properties and, therefore, are not within ICNIRP's remit and not addressed in this statement.

INCREASING USE OF SWL SOURCES

Artificial lighting technology has undergone rapid changes over the past 20 years (Pattison et al. 2018). Until about 50 years ago, the most common electric light source in people's homes was the incandescent bulb. This began to change when fluorescent lamps were introduced due to their greater energy efficiency in the 1960s. More recently, it was the LED that was touted as the "lamp of the future" due to its significantly higher energy efficiency and projected longer life (ibid). LEDs are now widely available and appear to be the light source of choice for consumers.

Our modern society allows for increasing exposure to light in the evening, significantly more than humans have been exposed to for the past approximately 300,000 years of evolution. In the past couple of decades, the use of mobile devices, e.g., smartphones, laptops, and tablets has increased exponentially, potentially resulting in a significant amount of light entering our pupils after daylight hours (Tosini et al. 2016). Cajochen et al. (2011) reported that, in 2010, 1.6 billion computers, TVs and mobile phones were sold globally, which illustrates that large numbers of individuals are spending time in front of such light-emitting devices worldwide. In fact, the exposure to artificial light at night has been estimated to have increased annually by 3% to 6% in the past few decades (Holker et al. 2010). Devices that incorporate LEDs in their displays emit proportionally more SWL than do traditional light sources (ANSES 2010), thus their increased usage can lead to increased exposure to SWL.

SPECTRAL EMISSIONS OF TRADITIONAL COMPARED TO MODERN LIGHT SOURCES

The emission spectrum from traditional incandescent lamps and the sun are relatively smooth compared to the spectra from fluorescent lamps or LEDs (Fig. 1).

Fluorescent lamps emit light through the excitation of a phosphor coating inside the bulb/tube, producing a spectrum that appears white. Most "white" LEDs combine a blue LED (peak emission in the 450–470 nm range) and a yellow phosphor (peak emission in the range of 500–640 nm with a peak at 580 nm). White light can also be approximated by employing multiple single-color LED chips that are combined to produce a spectrum that appears white, but this is more commonly used in displays (Tosini et al. 2016; ICNIRP 2020). In addition to their use as lamps in general lighting, LEDs are also the dominant light source in backlit tablet displays, smartphones, computer monitors and large television sets (Tosini et al. 2016). O'Hagan's group reported on the spectral emissions from LEDs, computers, tablets and smartphones in 2016 (O'Hagan et al. 2016). The SWL content of the LED lamps was similar to that of the incandescent lamps, computer monitor and tablets, while the

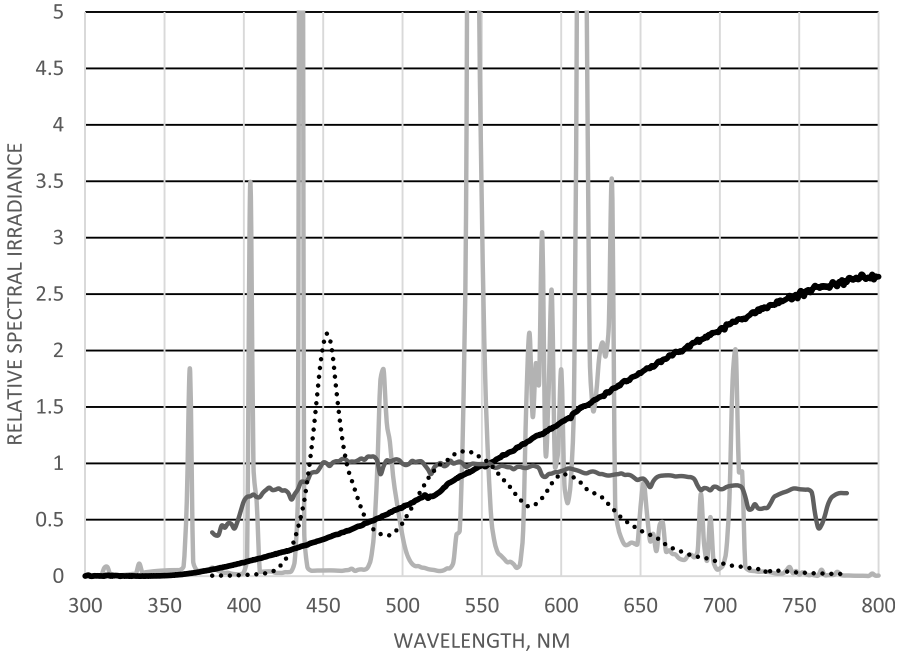

Fig. 1. Relative spectra (each source normalized to 1.0 at 555 nm) of a compact fluorescent lamp (CFL) (grey solid line), a 100 W incandescent lamp (heavy black line), a smartphone with white screen at full power (O'Hagan et al. 2016) (dotted black line) and a solar spectrum at 13:00 h from Ishigaki, Japan (Okuno 2008) (dark grey solid line).

smartphones emitted a level of SWL of about 2 times higher (ibid). Fig. 1 shows the relative spectra [all normalized to 1.0 at the peak daylight (photopic) sensitivity wavelength of 555 nm] of the sun, an incandescent lamp, a compact fluorescent lamp (CFL), and a smartphone. However, some LED products, e.g., handheld flashlights (known as "torches" in some countries), have stronger emissions in the SWL range than those evaluated by O'Hagan's group (ICNIRP 2020; Landry et al. 2021). Conversely, the SWL component of some LED sources has been reduced from what it was at their initial introduction—at least in some countries—possibly as a result of consumer pressure (Hao et al. 2022).

BIOLOGICAL MECHANISMS ASSOCIATED WITH SWL EXPOSURE

Light is necessary for human vision, but it also exerts a wide range of effects on mammalian physiology and behavior beyond vision, including effects on the neuroendocrine system and the synchronization of circadian rhythms to the environmental light-dark cycle (Fisk et al. 2018). The peak sensitivity for these effects is at approximately 480 nm, within the SWL wavelength range (Lucas et al. 2014; Prayag et al. 2019; Brown 2020). This is significantly shorter than the peak spectral sensitivity for daylight vision, which occurs at 555 nm.

The effects of light on human physiology are thought to be mediated through the retina by specialized intrinsically-photosensitive retinal ganglion cells (ipRGC) containing the photopigment melanopsin (Provencio et al. 2000; Hattar et al. 2002). The ipRGCs project to the suprachiasmatic nuclei (SCN), the central circadian pacemaker, as well as to other important brain regions implicated in alertness, sleep, and mood regulation. These effects are separate from other aspects of vision mediated by photoreceptors (i.e., rods and cones), as circadian effects can be observed in some blind individuals (Uchiyama and Lockley 2015; Hatori et al. 2017) and, thus, have been called "non-visual" or "non-image forming" effects. Such terms have come to encompass a growing list of acute effects of light, such as pupil constriction, suppressed pineal melatonin production, increased heart rate, and core body temperature, to name a few (SCENIHR 2012). Therefore, these types of effects have also been referred to as "intrinsically-photosensitive retinal ganglion cell (ipRGC)-influenced light (IIL)" responses by the International Commission on Illumination (CIE 2018). We will use IIL to describe the sleep-related, circadian, neuroendocrine, and neurobehavioral effects of light on humans in this Statement.

The last two decades have seen major advances in our understanding of the retinal photoreceptors that mediate IIL responses to light, as well as the neural pathways and molecular mechanisms by which circadian rhythms are generated and adjusted/entrained to the external light/dark cycle (Blume et al. 2019). Lucas et al. (2014) have proposed a new strategy for measuring IIL by combining the response to 5 photoreceptors in the retina: the S-cone, M-cone and

L-cone photopsin, melanopsin, and the rod opsin. Interestingly, a recent detailed analysis of the sensitivity of human circadian, neuroendocrine and alerting responses to ocular light used in studies performed to date concludes that the melanopsin absorption spectrum provides the best available metric to predict melatonin suppression and, thus, circadian rhythm disruption (Brown 2020).

PHYSIOLOGICAL EFFECTS OF SWL EXPOSURE

As explained above, the effects on the neuroendocrine system and circadian synchronization of human melatonin rhythms is particularly sensitive to SWL. In addition, such light might have the potential to reduce evening sleepiness by an alerting effect, suppress melatonin levels, and consequently affect sleep quality and duration, which over time may negatively impact human health. Human experimental studies have tested effects of SWL exposure on melatonin, alertness, and sleep, whereas long-term consequences on health have been studied in epidemiological studies.

Experimental studies on the effects of SWL exposure on alertness or sleepiness have shown conflicting results. This is evident from the most recent systematic reviews (Souman et al. 2018; Xu and Lang 2018; Mu et al. 2022; Silvani et al. 2022) assessing the effect of SWL on these outcomes. Mu et al. (2022) performed the only review with a meta-analysis. They found that broadband light with higher correlated color temperature (CCT), i.e., with a higher proportion of shorter wavelengths, compared with light with lower CCT, more effectively improved both subjective alertness and alertness assessed objectively by performance tests. However, they did not reveal any statistically significant difference for any of these outcomes when comparing monochromatic or narrow-band SWL with long wavelength light. These analyses combined studies irrespective of time of day of the exposures. In addition, when assessing effects of any light intervention (change in spectrum and/or intensity), Mu et al. (2022) found statistically significant effects both for daytime and nighttime exposures, but not for whole-day exposures. Souman et al. (2018) and Xu and Lang (Xu 2018) specified type of light intervention and time of day for the applied exposures of the included studies. For studies that examined daytime exposure, only two of the nine studies included by Souman et al. (2018) resulted in a statistically significant subjective alerting effect. There was almost no difference in the number of studies indicating an objective altering effect vs. those indicating no effect.

For studies that examined nighttime (evening and night) exposure, the number of those reporting increased subjective alertness was approximately the same as the number reporting no statistically significant result. Xu and Lang (2018) found that most studies reported an objective alerting effect, while Souman et al. (2018) included slightly more studies with no effect of exposure compared to those showing an increase in objective alertness. One reason for the inconsistent findings for objective alertness may be that Xu and Lang (2018) included studies using EEG and eye movements, while Souman et al. (2018) included studies using performance tests. In summary, the results by Souman et al. (2018) and Xu and Lang (2018) indicate that nighttime exposure to SWL may influence alertness slightly more than daytime exposure. Silvani et al. (2022) only reviewed studies that examined effects of SWL but did not specify the time of day of the exposures. They found that more studies reported alerting effects vs. no effects, and this was similar for both subjective and objective alertness. It should also be noted that some of the included studies found an effect for subjective but not objective alertness or vice versa (Xu and Lang 2018), and a few studies reported reduced rather than increased alerting effects from exposure to SWL (Souman et al. 2018; Silvani et al. 2022).

In addition to assessing immediate alerting effects, Silvani et al. (2022) reviewed effects of exposure to SWL on sleep, and Xu and Lang (2018) included two studies where effects on sleep were assessed. More than half of the studies reported no effect of prior exposure to SWL on sleep quality, latency or duration. A few studies reported impaired sleep and still fewer reported improved sleep for these endpoints. SWL exposure before sleep also resulted in mixed result on daytime sleepiness. While one study reported increased sleepiness the other study found no effect (Xu 2018). Interestingly, a recent study by the Cajochen group (Blume et al. 2022) found that although melatonin was suppressed by nighttime exposure to SWL, this did not translate to altered levels of vigilance or sleepiness. The authors suggest that an interaction between melanopsin and cone-rod signals needs to be considered.

Reasons for the varying results between individual studies may be differences in the applied exposures (intensity, wavelengths, duration, and timing), in the control light conditions, and in the outcome variables. Another reason may be effects of moderating variables, which are factors, like prior light exposure, and age and sex of the participants, that may modify the effect of the SWL exposure. For example, Xu and Lang (2018) found that light exposure during the daytime may reduce the alerting effect of SWL at night, which is also suggested by others (Souman et al. 2018; Brown 2020). This is consistent with findings of similar effects of daytime light exposures on melatonin level (Souman et al. 2018; Brown 2020). Other factors, e.g., the activity level of the individual study participants, also appear to modify the alerting effect of light exposure (Xu and Lang 2018). Furthermore, several methodological issues may have biased results in some studies. Among these issues are low number of participants resulting in low

statistical power (Souman et al. 2018; Silvani 2022), non-blinded exposure conditions (Xu and Lang 2018; Mu et al. 2022; Silvani et al. 2022), missing control of carryover effects in studies with crossover design (Xu and Lang 2018), and not applying randomization of the order of the compared light exposures (Souman et al. 2018; Silvani et al. 2022). Another major issue is that several studies used control conditions (with less or no SWL) that had lower light levels compared to the exposure with SWL (Souman et al. 2018). Thus, the effect of light levels and spectra could not be separated.

Since only healthy adults participated in the included studies, the findings of the systematic reviews cannot be generalized to the entire population. Other studies suggest that individual variations related to chronotype (Xu and Lang 2018) and polymorphism (Souman et al. 2018) may be important for the sensitivity to SWL exposure. The age of the individual is also a factor, with adolescents being more sensitive to SWL exposure effects than adults (Figueiro and Overington 2016; Nagare et al. 2019). This has been shown to be due to the fact that adolescents have a higher transmittance of SWL through their natural lenses than do adults (Brainard et al. 1997). Since the transmittance of the natural lens decreases with age, especially in the SWL part of the spectrum, and pupil size decreases with age, children and infants would be expected to be even more responsive to SWL exposure than are teenagers or adults (ibid, Eto et al. 2021).

In total, the evidence is inconsistent, with many studies indicating possible effects of SWL on alertness or sleep, and many others not supporting such effects. The varying results, which may be due to differences in applied exposures, outcomes and modifying variables but also to methodological issues, make it difficult to draw a general conclusion about effects of SWL on alertness or sleepiness. However, as also suggested by Souman et al. (2018), for some individuals and under certain circumstances SWL might reduce sleepiness and thereby have a negative effect on sleep. High quality experimental studies, especially studies that allow for the construction of dose-response curves, are needed to confirm whether that is the case.

POTENTIAL ADVERSE EFFECTS FROM SWL EXPOSURE

There is a large body of evidence from epidemiological studies that insufficient sleep, including that caused by circadian system disruption, is related to a spectrum of adverse health effects ranging from decline of neurocognitive function to anxiety and mood disorders to endocrine dysfunction (Grandner 2017). Circadian disruptions, including decrease of melatonin levels, have been suggested to play an important role in development of chronic diseases and conditions such as cancer (SCENIHR 2012). A recent systematic review (Urbano et al. 2021) found a positive association between exposure to light at night and breast cancer. However, the majority of studies that have assessed circadian disruption due to exposure to light have been conducted in shift workers. These are summarized in comprehensive reviews of shift work in relation to cancer by the International Agency for Research on Cancer (IARC) (2019) and by the National Institute of Environmental Health Sciences (NIEHS) National Toxicology Program (NTP) in 2021 (NTP 2021). In these studies, shift workers' exposure to light during biological night has been taken for granted without direct measurements of their light exposure. Furthermore, it is often assumed that shift workers are predominantly exposed to SWL, but no epidemiological studies have made direct measurements of the wavelength of the light sources to verify and quantify this. As also noted by NTP, it is not possible to evaluate whether observed adverse health effects (here increased cancer risk) were caused by exposure to light at night, to sleep disturbances, to meal timing (alone or in combination), or some other factors related to shift work. Although epidemiological studies have addressed different light exposure timing and levels, and evaluated effects on, e.g., circadian disruption, sleep quality, diabetes (Obayashi et al. 2020), or breast cancer (Stevens 2009), the studies generally failed to assess effects specifically from SWL exposure. Thus, although there are many concerns about potential adverse health effects of excessive exposure to SWL (especially at night) caused by circadian rhythm disruption and sleep deprivation, epidemiological studies of long-term effects of chronic SWL exposure *per se* on human health are lacking.

LIMITATIONS OF RESEARCH PERFORMED TO DATE

Many currently published studies in this area have relied on photometric quantities (e.g. illuminance) when recording IIL effects from light exposure (Spitschan et al. 2019). This can lead to misleading results since the peak sensitivity for the photopic system is at 555 nm whereas the peak sensitivity for IIL effects is at 480 nm. The recently published CIE S026 standard provides five weighting functions that can be used to evaluate effects on the ipRGC system (CIE 2018). In addition, since illuminance or irradiance are not directly relatable to retinal irradiance, it is advisable to use radiance measurements as these quantities are directly related to retinal irradiance. However, if studies are conducted to compare results of light sources with identical geometry, it is acceptable to measure spectral irradiance (instead of spectral radiance) and then apply the five CIE S026 (CIE 2018) weighting functions. In fact, a recent meta-analysis by Cajochen et al. (2022) found that

melanopic equivalent daylight illuminance was a robust predictor of evening light exposure effects on sleep.

Apart from the problems with dosimetry, there are a number of other limitations with the currently available research on the potentially adverse effects of SWL exposure. Experimental studies have not usually been blinded and exposure awareness may have biased any reported effects. Although the influence of prior light exposure, age, and sex has been previously investigated, lack of consideration of these modifying variables and confounding factors remains a limitation in many of the experimental studies.

In epidemiological studies the main limitation is appropriate exposure assessment since personal exposure to SWL has not been directly assessed in previous studies. Further, the variability in exposure metrics used in epidemiological research to date makes the comparison and pooling of results difficult. Although confounding factors have been variably addressed in previous studies, uncontrolled confounding due to various occupational, personal, and lifestyle factors remains a methodological problem for much of the epidemiological research.

CONCLUSION

Exposure to SWL has been shown to interfere with some IIL responses in a wavelength-dependent manner in some studies. It has generally been assumed that exposure to SWL at night will cause alertness and affect sleep quality. However, due to limited data and conflicting results regarding effects on alertness, sleepiness, and sleep it is not possible to reach a conclusion about effects on these outcomes. This is the case for both nighttime and daytime exposure. Thus, more high-quality experimental studies are needed to answer the question of whether SWL exposure at night affects alertness and sleep more than exposure at other times of the day. With regards to potential long-term adverse effects from chronic, nighttime exposure to SWL, there is also not a sufficient number of well-conducted epidemiological studies available currently to draw any conclusions. In general, the current literature is limited due to methodological shortcomings, mentioned earlier. Thus, there is a pressing need for high quality experimental and epidemiological studies that carefully measure SWL exposure and health outcomes. ICNIRP recommends that an analysis of data gaps be performed to delineate the types of studies needed, the parameters that should be addressed, and the methodologies that should be applied in future studies so that a decision about the need for exposure guidelines can be made. In the meantime, ICNIRP supports the recommendations for future studies in the Appendix.

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APPENDIX. RECOMMENDATIONS FOR FUTURE STUDIES

In experimental studies, the light exposure should be determined as follows:

1. Measure the spectral power distribution of light sources used, timing and duration of exposure.
2. It is preferable to use radiance measurements as this quantity is directly related to retinal irradiance.
3. Use a standard for ipRGC-influenced responses to light: melanopic EDI, such as that defined by the CIE (http://www.cie.co.at/files/CIE%20Position%20Statement%20-%20Proper%20Light%20at%20the%20Proper%20Time%20%282019%29_0.pdf and http://www.cie.co.at/publications/cie-system-metrology-optical-radiation-iprgc-influenced-responses-light-0).
4. Measure the light exposure in the vertical plane, at the subject's eye, if possible. Consider using a hood on the detector to limit the measured light to a 1 steradian field-of-view (Sliney 2019).
5. If studies are conducted to compare results of light sources with identical geometry, it is acceptable to measure spectral irradiance using an appropriate FOV.
6. Record pupil size.

In addition, the studies should be:

1. Blinded, by comparing different light intensities instead of light vs no light.
2. Include objective measurements of effects, e.g., EEG recordings, performance tests.
3. Include a sufficient number of participants to allow for detection of small to medium size effects.
4. Designed to include various exposure intensities, to explore dose-response relationships.

In epidemiological studies, it is important to monitor actual personal exposure and not rely on satellite measurements of light levels. A long-term, prospective cohort study would be desirable.

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