The power of healthy daytime lighting in indoor settings

Melanopic lighting advances and office applications

Signify

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Summary

Next to being essential for vision, light has important functions beyond vision, often referred to as non-visual or non-image forming effects/responses. Light regulates our physiology (hormones), behaviour, mood and circadian rhythms, thus controlling our ability to remain awake and concentrated (for work/learning) or to fall (or remain) asleep. The importance of circadian rhythms for health and well-being is underlined by the 2017 Nobel Prize for Physiology or Medicine which was awarded jointly to Jeffrey C. Hall, Michael Rosbash and Michael W. Young for their research on molecular mechanisms controlling the circadian rhythm and sleep-wake patterns.

At the beginning of the 21st century a new retinal photoreceptor was discovered, the intrinsically-photosensitive retinal ganglion cell (ipRGC). In addition to receiving extrinsic signals from rods and cones, these cells have an intrinsic sensitivity to light that is based on the photopigment melanopsin. The light sensitivity curve of this melanopsin-based photoreception peaks at around 480 nm [1-5]. Light that effectively activates the melanopsin-based photoreception of ipRGCs secures strong biological responses [6-8], and will be denoted as 'melanopic light' in this paper.

Most of our indoor environments leave us light-deprived as compared to the natural light exposure during daytime outdoors. Civil twilight on a semi-overcast day has a maximum (horizontal) illuminance of about 400 lx [9], and as such one could say that an indoor illuminance of 500 lx horizontally (as for instance specified in the EU standard for workplaces [10]) is rather modest and resembles civil twilight. Insufficient daytime light exposure compromises vitality, mood, activities, and health [11-18]. Daytime light exposure is, together with nocturnal darkness, by far the most important and powerful biological signal to regulate the timing, robustness and strength of the body clock that structures our intrinsic circadian rhythmicity [6, 19, 20].

The following factors are important determinants for the ability of light to regulate the body clock:

1. timing of light exposure: early morning light advances the body clock (this facilitates an earlier bedtime and sleep onset), while evening light delays the body clock (this facilitates a later bedtime and sleep onset) [21].
2. illuminance: higher light levels result in stronger effects (as long as the threshold for saturation is not yet reached [6, 22].
3. spectrum: effects are stronger when the spectrum has more melanopic content (as long as the threshold for saturation is not yet reached) [6].
4. exposure duration: increasing exposure duration increases effect size (in a non-linear fashion and as long as the threshold for saturation is not yet reached) [23-25].
5. light history: more daytime light exposure can reduce the (sleep-disruptive) impact of evening/nighttime light exposures [26-29].
6. the application context: interindividual differences in light sensitivity are reported to be large [30] and different populations (such as children, seniors, shift workers, healthcare patients) have different lighting needs [31-33].

A robust body clock is supportive for daytime alertness and performance and reduces the propensity to be awake and functioning at times that our body clock and physiology is programmed to support sleep. A stronger, more natural and outdoor-like light-dark cycle improves the strength of the 24-hour rhythm of the body clock and its alignment with the behavioral sleep-wake cycle, which is supportive for general health and productivity [34-38].

Together with the more than 100 years of in-depth knowledge on lighting applications and technological innovations in spectral engineering, optical design, controls and connectivity, the above insights open up the opportunity to design healthy indoor environments and lighting solutions that produce similar benefits as the natural (outdoor) lighting conditions.

Traditionally, the design of workplace lighting in general, and office lighting in particular, has been largely driven by requirements that relate to visual functions, experiences and comfort. The lighting is primarily designed to ensure a good performance and comfort on visual tasks.

With the recent insight that light plays a much bigger role than vision only, two new quantities have been defined to specify the lighting environment with respect to its ability to support health and well-being aspects [39]:

1. The effectiveness of a lighting condition to activate melanopsin-based photoreception and drive ipRGC responses can be expressed in terms of the absolute quantity melanopic equivalent daylight illuminance (melanopic EDI). During daytime the guideline for melanopic EDI is: the more, the better, although this should not supersede existing guidelines [12]. Based on a comprehensive analysis of the sensitivity of human non-visual responses to retinal light exposure Brown et al. [11] recommend a minimum melanopic EDI of 250 lx at the eye for daytime indoor environments (measured in the vertical plane at ~1.2 m height) as to promote optimal physical and mental health and performance.

2. The melanopic daylight efficacy ratio (melanopic DER) is a dimensionless relative quantity that describes a spectral characteristic of a light source and expresses the melanopic activation of a (test) light source as compared to a reference light source that emits a daylight spectrum (D65) and produces the same photopic illuminance as the test light. For instance, a test light with a melanopic DER of 1.25 or 0.75, has a melanopic activation (per lumen) that is 25% more or less as compared to daylight D65, respectively.

Both these quantities can be used in combination with existing criteria that target adequate visual function and comfort. The importance of ipRGC-dependent, non-visual responses to light for people's health, performance and well-being and the daytime light deficiency induced by our modern indoor lifestyle is increasingly recognized by both scientists and policy makers. The increasing number of projects with building certifications like WELL [40] emphasizes the growing focus on optimizing health and well-being within the built environment. A recent literature study demonstrated that better building designs and operation strategies (e.g. improved ventilation, enhanced lighting conditions, green building certification measures) provide benefits to multiple organizational productivity metrics at levels similar to other popular corporate strategies that are implemented at the employee level [41]. However, the design and implementation of lighting solutions that target both the visual and non-visual functions of light is complex: outcomes can strongly depend on the temporal and spatial illumination patterns as well as on the individual characteristics and lifestyle of the user. As a consequence user benefits cannot always be predicted from product features alone. In addition, decision makers can be quite pluriform in their office lighting design goals and requirements. So far, the existing knowledge on light and its important role for health has not (yet) been translated into requirements or specifications for melanopic lighting that have gone through the full consensus and balloting process required for international standardization in either CIE or ISO.

Scientists continue to investigate the pathways by which ocular light exposure influences human health and well-being and it needs to be monitored whether the requirements above need to be adjusted as new insights become available. However, in the mean time, the suggested melanopic ranges can facilitate decision making to transform office spaces towards better building design, space utilization, occupant comfort and well-being. For the past decades, the lighting industry has been working to improve energy efficiency of lighting for a better world. The melanopic lighting systems of Signify are designed to support people's biorhythm and well-being during the day by means of energy-efficient human-centric or integrative lighting solutions that bring the power of natural light into our homes and offices.

In this paper the latest scientific insights on how light affects people's sleep, health and well-being are combined with in-depth lighting application knowledge of Signify with the aim to provide guidance and recommendations for the application of melanopic lighting.

1 Introduction

Many adults (office workers) spend a large part of their days in an office environment. The physical characteristics of the office, such as lighting, temperature, air quality and auditory noise levels, play an important role in the well-being and performance of office workers [41]. New guidelines and building certification programs, such as the 'WELL Building Standard' (https://www.wellcertified.com/), recognize this and set requirements for office buildings with the aim to improve the life of their inhabitants. As far as lighting is concerned, this trend is also driven by recent discoveries on how light affects human health, well-being and functioning as well as by new technological developments in solid-state lighting.

Traditionally, the design of workplace lighting in general, and office lighting in particular, has been largely driven by vision-related specifications and requirements. Minimum target levels to prevent visual discomfort are provided by for instance the European standard EN12464-1 for light planning in workplaces [10].

Since about 20 years ago, we know that the brain has dedicated pathways for 'non-visual' or 'non-image forming' effects of light, such as the circadian regulation of sleep-wake patterns, body temperature and hormone levels. As it turns out, these effects involve a newly discovered photoreceptor in the human eye, namely intrinsically-photosensitive retinal ganglion cell (ipRGC). The light sensitivity of this photoreceptor is based on the photopigment melanopsin and peaks at around 480 nm [1-5].

At the same time, the rapid developments in light emitting diode (LED) solid-state lighting and connectivity allow manufacturers to be much more flexible in designing their lighting systems, and to reduce the carbon footprint for operating the building. The renewed focus on employees' well-being, the technological innovations in light and lighting and the recent scientific advances in physiological effects of light on human health and well-being has inspired lighting manufacturers to rethink how to illuminate indoor office environments such that the lighting installations provide a similar biological potency during daytime hours to natural outdoor daylight (see Figure 1). Lighting solutions and installations that adopt both the visual and non-visual effects of light to reinforce positive human outcomes are often referred to as integrative or human-centric lighting.

This paper covers the most recent scientific insights on how light affects people's sleep, health and well-being are combined with in-depth lighting application knowledge of Signify with the aim to provide recommendations for the application of melanopic light. The next section explains the importance of daytime light for people's health and well-being. Section 3 elaborates on the current understanding of human non-visual responses to light and the important role of ipRGC photoreception in these responses. Also, the results from various lighting intervention studies in (simulated) office environments will be briefly highlighted. In Section 4, the two newly standardized light quality parameters, melanopic equivalent daylight illuminance (EDI) and melanopic daylight efficacy ratio (DER), are introduced to quantify the ability of a lighting solution to activate ipRGCs and drive important non-visual responses. Section 5 brings this information together and includes the recommendation for a melanopic equivalent daylight illuminance of at least 250 lx during daytime for office environments.

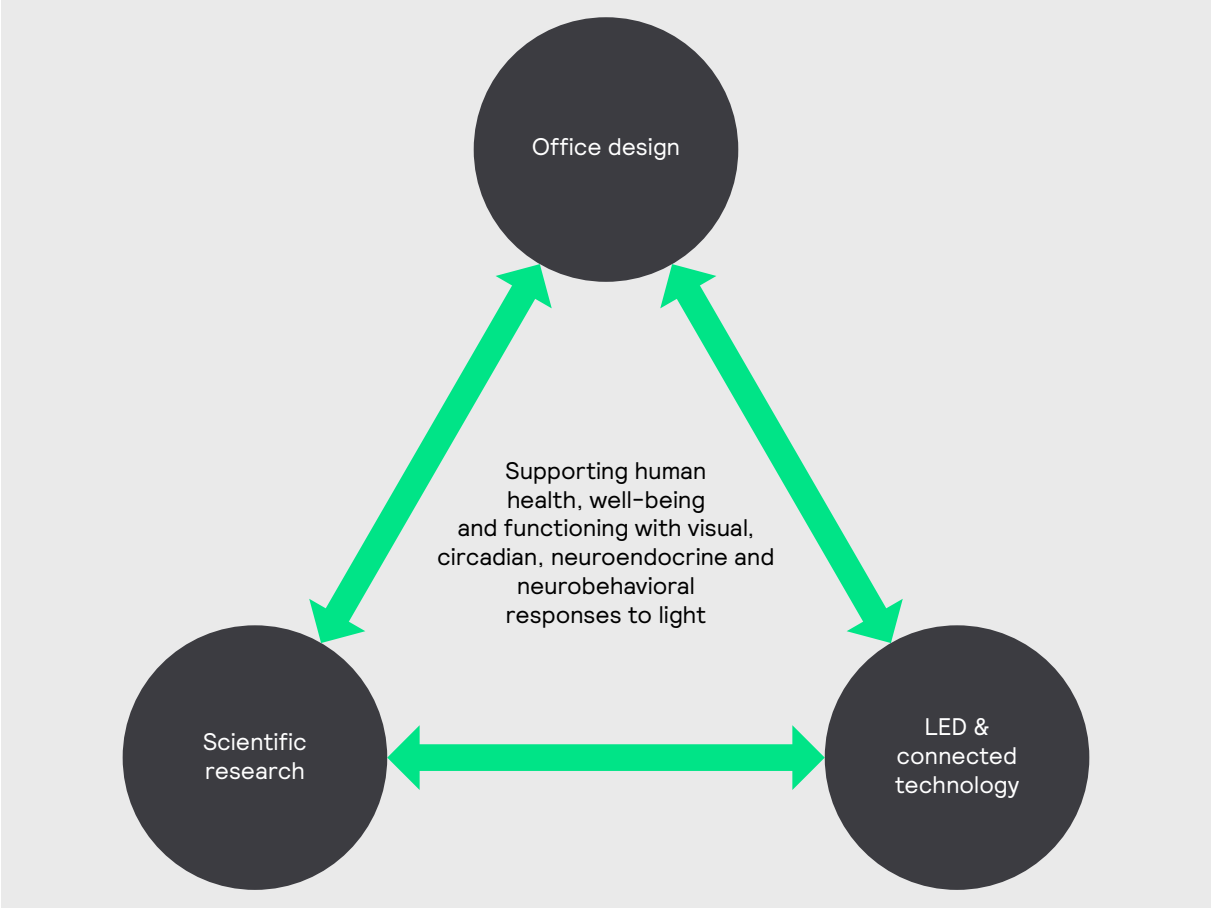


Figure 1: New focus on health and well-being in office design goes hand in hand with LED technology and scientific research on the visual and non-visual effects of light on humans to improve working environments for office employees.

2 Importance of daylight

"Light affects our circadian rhythms more powerfully than any drug" **Czeisler [42]**

Health and well-being matter to everybody and yet not everyone realizes just how big a role light can play. We take light for granted, but should we? Like plants need light to grow, also people need light. Light with the right quantity, the right spectral content and at the right time of the day allows us to perform, interact, sleep develop and grow.

People evolved under the natural radiation of the sun. Because of the earth's rotation around its axis, we have a 24-hour light-dark period. As for all organisms, this puts critical demands on the ability to adapt to this 24-hour light-dark cycle and its seasonal variations. Proper anticipation and adaptation to daily and annual cycles of the environment is for instance highly relevant for food gathering, predator avoidance, thermoregulation, reproduction, hibernation and migration. In the course of evolution, humans, along with other mammals, developed a central internal clock in the brain that uses environmental signals, called zeitgebers, to generate an internal rhythmicity that is well aligned with the 24-hour cycles in our environment. Retinal light exposure is the most important and powerful zeitgeber signal in humans [43, 44] and light affects our circadian rhythms more powerfully than any drug [42]. This implies that adequate light exposure in terms of timing, intensity, directionality and spectral composition is an important determinant of human health, functioning and well-being. The natural radiation of the sun and its 24 hours rhythm on our planet, with a dark and a bright period, can be seen as a perfect benchmark for optimal light exposures in humans.

Different photoreceptors are present in the human body, for instance within the skin and eyes. These photoreceptors absorb specific wavelength ranges within the natural radiation of the sun and subsequently activate a wide variety of bodily processes. The schematic representation in Figure 2, adapted from [45, 46], visualizes the relationships between retinal light exposure, the visual and non-visual pathways and human outcomes.

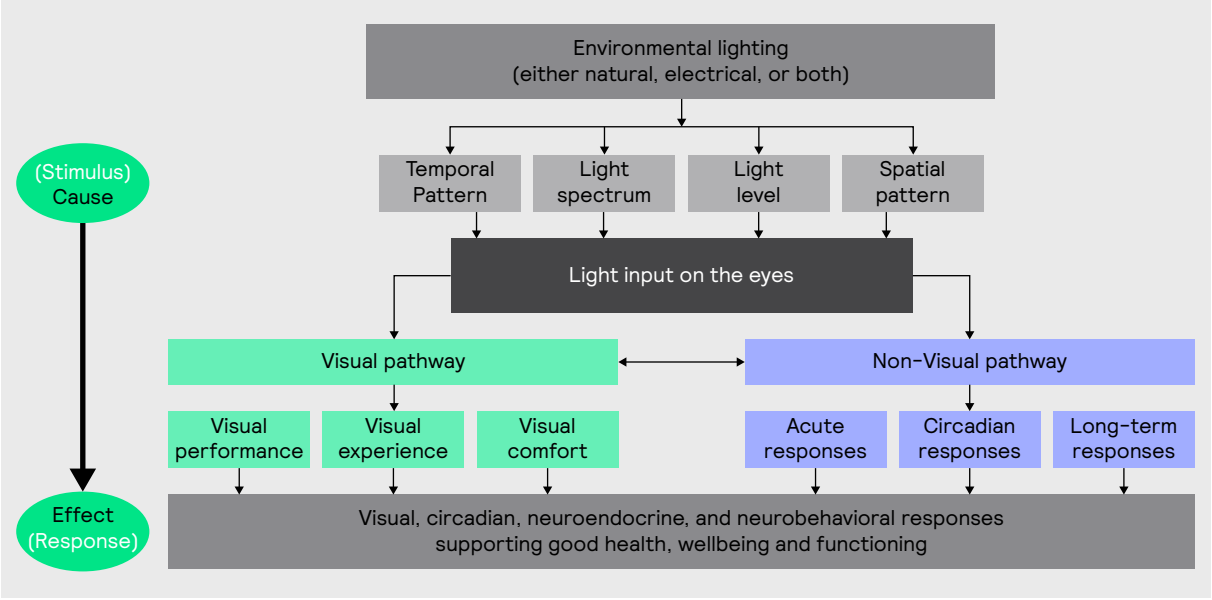


Figure 2: A schematic representation of the mechanism how light with the right quantity, the right spectral content and at the right time of the day supports good health, well-being and functioning.

The temporal pattern in the upper part of Figure 2 relates the timing and duration of a light stimulus/exposure; spatial pattern refers to the spatial distribution of light within the space; light spectrum refers to the spectral power distribution (SPD) that governs color qualities, and light level refers to the quantity of light in radiometric or photometric units. These four factors are main determinants of the visual quality and biological potency of the light stimulus.

A visual response is defined as an eye-brain response that enables sight and contributes to (i) visual performance, (ii) visual experience (this includes certain emotional responses), and (iii) visual comfort (or discomfort/glare). Non-visual responses (often also denoted as non-image forming (NIF) effects of light) include various biological, and/or physiological responses, for instance circadian responses (i.e. responses that affect the circadian rhythm; many internal biological processes display a rhythmicity with a roughly 24 hours period, the sleep-wake cycle is one example of such a circadian rhythm), neuroendocrine responses (how light influences hormones, for instance the production of our sleep-supporting hormone melatonin) and neurobehavioral responses (effects of light on the nervous system and human behavior).

In general, sufficient retinal daytime exposure is important for the followings, with scientific proof points listed hereafter:

- vision, sleep and mood,
- vitality and alleviating stress
- daytime functioning and cognitive performance
- circadian health so that bodily processes are in sync with each other and in sync with the activity at hand.

Scientific proof points on the benefits of adequate daytime light exposure

* Daytime light exposure supports vitality and alleviates distress in healthy subjects [16]
* Daytime light exposure supports daytime functioning, cognitive performance and alertness in healthy subjects [47-49]
* Daytime light exposure supports sound sleep in healthy subjects [18].
* Daytime light exposure entrains, strengthens and stabilizes circadian rhythms, regulates sleep timing and enhances nocturnal melatonin levels [15, 38]. Adequate entrainment means better sleep and higher alertness, and a better cognitive state and mood during wakefulness [50], and supports metabolic function [34, 35, 51].
* Daytime light exposure reduces sensitivity to the sleep disruptive action of late-evening light exposures [26-29].
* Daytime light exposures support a better alignment between the sleep-wake cycle and the natural 24-hour rhythm of the body clock thus supporting general health and productivity [34, 37, 52].
* Increasing time spent outdoors in bright daylight is known to be protective against myopia [53-56].

As mentioned earlier, humans are equipped with a light sensing machinery that ensures that bodily processes are properly coordinated and synchronized to the environmental 24-hour day-night cycle. Although the importance of daytime light for human health and well-being is well established, our modern indoor lifestyle has profoundly and irreversibly changed our work and social schedules to become much more variable, irregular, and disconnected from the biological clock and the natural light-dark cycle. Reduced exposure to daytime (sun)light and increased exposure to electrical lighting in the evening and at night leads to circadian misalignment and late sleep timing [37, 38, 57]. A weak and/or irregular circadian rhythm is a risk to people's health: it can lead to a reduced sleep quality, depression, weight gain and even cancer [58, 59]. Sleep deficiency is associated with an increased risk of obesity, diabetes, cardiovascular disease and depression [42].

Moreover, people who prefer later bedtimes have more irregular sleep patterns and a higher risk of metabolic and mental health impairments [60-64]. Recent research shows that 1 hour of misalignment between social and biological rhythms can have significant repercussions for sleep, general health and economic outcomes [35].

Scientific proof points on risks of insufficient daytime light exposure

* Individuals with low exposure to light during the day report a lower subjective sleep quality [14, 65, 66] and sleep deficiency is a known risk-factor of obesity, diabetes, heart disease and depression [42].
* A low exposure to light during the day is related to an increased risk of (minor) depressive symptoms [14, 67].
* Less daytime light exposure is associated with more complaints of sleepiness [66].
* Less daytime light exposure is associated with a later chronotype (i.e. a preference for later bedtimes and being an "evening person") [18, 37, 68, 69]. Later chronotypes have more irregular sleep patterns and a higher risk for impairments in metabolic health and mental health [60-64].

3 The discovery of the ipRGC and subsequent field studies and translational research

"Collectively, our data demonstrate widespread utility of melanopic illuminance as a metric for predicting the circadian impact of environmental illumination. These data therefore provide strong support for the use of melanopic illuminance as the basis for guidelines that seek to regulate light exposure to benefit human health and to inform future lighting design" **Brown [6]**

At the beginning of the 21st century a new retinal photoreceptor was discovered, the intrinsically-photosensitive retinal ganglion cell (ipRGC). Next to receiving extrinsic signals from rods and cones, these cells have and intrinsic sensitivity to light that is based on the photopigment melanopsin. Light that strongly activates the melanopsin-based photoreception of ipRGCs secures strong biological responses [6-8], and strongly regulates physiological and behavioral rhythms such as the sleep-wake cycle. Figure 3 presents a schematic representation of the eye and the different retinal photoreceptors. The rods and cones are located in the outer layer of the retina, closest to the choroid, while the ipRGCs are nested in the retinal ganglion cell (RGC) network located in the inner layer of the retina.

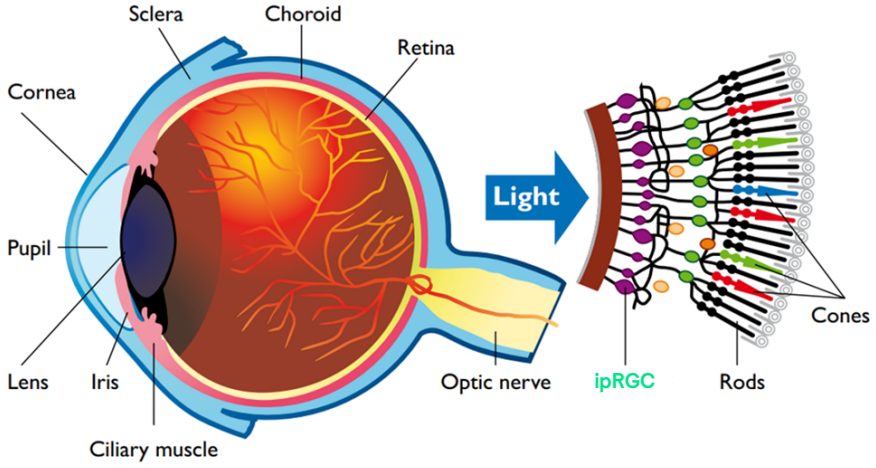


Figure 3: Schematic representation of the eye and the different retinal photoreceptors

The left image in Figure 4 displays the melanopic spectral sensitivity function of the melanopsin-based photoreception of ipRGCs together with the CIE standard daylight spectrum [72]. The melanopic sensitivity function peaks in the short wavelength range the visible spectrum, around 480 nm. Figure 4 (right) represents the normalized spectral sensitivity functions for all the five a-opic retinal photoreceptors as defined in CIE, 2018 [39]: L-cones (L-cone-opic), M-cones (M-cone-opic), S-cones (S-cone-opic), rods (rhodopic, based on the spectral luminous efficiency function for scotopic vision, V'(λ)), and the melanopsin-based photoreception of ipRGCs (melanopic). The spectral sensitivity functions are normalized to have a maximum value of 1. The spectrum of the CIE standard illuminant D65 [72] is taken as the reference source to define melanopic and other α-opic quantities in International Standard CIE S 026 [39].

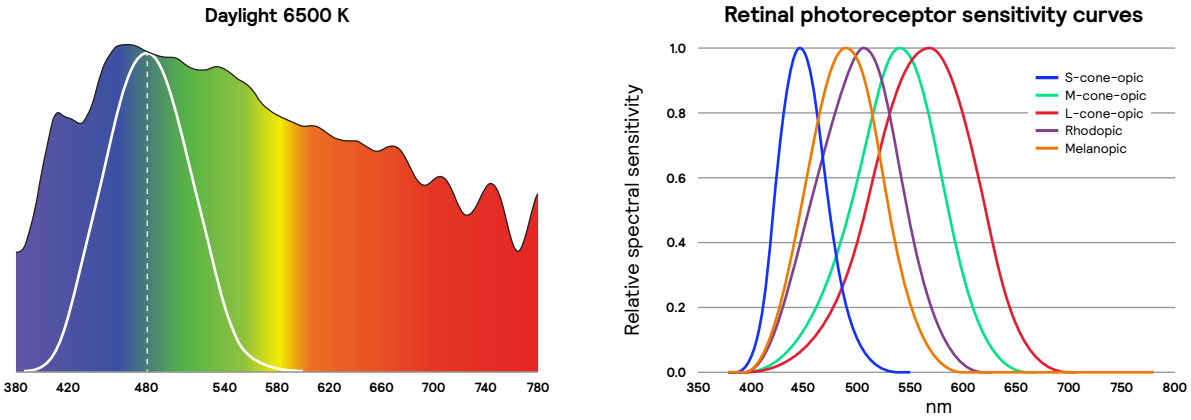


Figure 4: Left: Schematic representation the spectral sensitivity curve of the melanopsin-based photoreception of ipRGC, peaking around 480 nm plotted in the CIE standard daylight (D65) spectrum (white solid line). Right: The normalized spectral sensitivity functions for the five α-opic photoreceptors as defined in CIE, 2018 [39].

Light, and especially bright light with a high melanopic activity (i.e, enriched around the 480 nm range) is proven to be an effective and powerful signal to regulate the timing, robustness and rhythmicity of the body clock [11, 73] thus controlling our ability to remain awake and concentrated (for work/learning) or to fall (or remain) asleep. The central body clock in our brain is located in the SCN and this clock ensures that many cells and organs remain in sync with the natural dark-light cycle and with each other (see text box). The body clock is involved in the circadian regulation of our physiology (hormones) and behaviour. There are many more biological processes that are influenced by ipRGC photoreception. Scientists discovered, for instance, direct pathways to the mood and learning centres in the brain [74]

The central clock and circadian rhythms

Many cells and organs cells in the human body need input from the outside world for proper synchronization to the daily light-dark cycle. The central pacemaker, which is located in the suprachiasmatic nuclei (SCN) in the hypothalamus, just behind the eyes, plays a key role in this synchronization [75, 76].

The SCN has around 20,000 neurons and it is divided into a light-sensitive part and a non-light sensitive part [77, 78]. The non-light sensitive part drives our internal circadian rhythms without any external input, telling the body when to expect darkness or light. In contrast, the light-sensitive part of the SCN receives input from the eyes, and adjusts our internal clock to changing external circumstances, such as changes in daylength across the seasons.

Melatonin levels and the core body temperature are controlled by the body clock so that our body has an estimate of the external light-dark cycle [79]. This way the body clock controls a whole range of other processes in the body with 24-hour rhythms, such as heart rate, blood pressure and the release of hormones like cortisol and insulin [80] - all of which have a strong influence on the sleep-wake cycle.

The rhythmicity of the central biological clock (pacemaker) in our brain is regulated by light, and this clock is especially sensitive to light of wavelengths between 450 nm and 530 nm [19, 20].

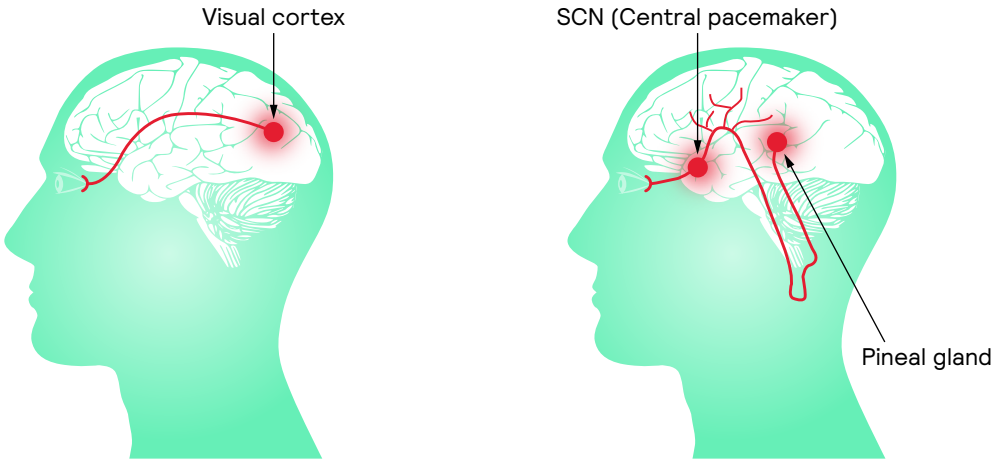


Figure 5: Schematic representation of the visual (left) and non-visual pathway (right).

The visual pathway is activated by the rods and cones and responsible for sending signals to the visual cortex (Figure 5 left). The visual cortex analyses the neural signals and constructs a conscious visual perception that people can interpret and put in context: vision. The non-visual pathway is strongly dependent on the melanopsin-based photoreception of ipRGCs. The ipRGCs send their signals to the suprachiasmatic nucleus (SCN) as visualized in Figure 5 (right). The SCN is situated in the hypothalamus, just behind the eyes and its function is to act as a central body clock or (circadian) pacemaker and to synchronize bodily processes, cells and organs to the natural dark-light cycle. The absence of melanopic light in the evening and at night enables the SCN to prepare the human body for darkness-related behavior: sleep. The SCN sends a "night" signal to the pineal gland, which then produces melatonin, the hormone that supports and consolidates our sleep. We typically fall asleep about two hours after the onset of melatonin secretion (in dim light conditions) [81, 82]. During sleep essential restoration processes and processes required for memory consolidation and cell repair are initiated [83, 84]. A higher activation of the ipRGC during the day provides a stronger regulation of the body clock and the sleep-wake behavior as compared to a low activation during the day. In general, having more melanopic light during the day:

- allows for an easy wake up on the next morning so we are better prepared to study or work,
- supports sound sleep at night, more daytime engagement, and a positive mood,
- makes you less sensitive to (sleep-disruptive) late-evening light, thus enabling a more rapid sleep onset (easier to fall asleep).

A recent study revealed that bright daytime light intensity enhances the amplitude and robustness of circadian rhythms in a diurnal rodent (Rhabdomys pumilio) by actually strengthening the SCN electrical activity pattern [85, 86]. The experiments also demonstrated that the animals were substantially less sensitive to evening light when exposed to brighter light during the day.

The discovery of the ipRGCs and their involvement in sleep-wake mechanisms, circadian health, and modulations in alertness, sleep and mood inspired researchers to conduct translational research in this field. Some first examples can be found in hospitals, care environments, and schools. A hospital patient room lighting system with brighter light (i.e. a high light intensity with a high correlated colour temperature (CCT)) during daytime was found to increase patients' sleep duration by almost six minutes each night compared to the standard lighting in a hospital setting [87]. Similarly, higher light levels in a care facility for elderly patients with dementia reduced cognitive decline and depression scores [32]. Finally, studies involving primary school children indicated that allowing the teacher to turn on a high intensity, high CCT light setting, resulted in a concentration and performance increase as compared to the control group, and also improved reading skills [88-90].

Translational research on office lighting interventions has yielded mixed results, and this might be attributable to the fact

that within office populations there can be large(r) inter individual differences with respect to prior light exposure, personal traits and sensitivity to light as well as to heterogeneity in sleep behavior, time spent outdoors and physical activity. Table I summarizes the findings of a literature study executed by Signify (2019) into the effects of lighting interventions that involved modulations in melanopic light within (simulated) office environments [91]. The interventions are generally realized by increasing CCT and/or illuminance on the task and reported as such. This literature study included laboratory and field studies with outcome parameters such as sleep, sleepiness, mood and vitality, performance and visual comfort.

An office lighting study by Viola reported higher positive mood and improved sleep under higher CCT (17000 vs 4000 K) [49]. Similar findings were reported by Figueiro and colleagues for high vs low circadian active light in the morning: they reported that having more circadian active light in the morning was associated with reduced depression and increased sleep quality [13]. Furthermore, enhancing daytime melanopic exposure by increased access to natural daylight in the workplace improved sleep and cognitive performance in office workers [92]. Finally, the review by Xiao et al [93] reported 4 publications [94–97] in which participants felt more alert in the ≥ 1000 lx condition compared to the 100–400 lx condition during the daytime. Last but not least, upon a data analyses from 19 laboratory studies that measured effects of light on alertness, melatonin suppression and circadian phase resetting Brown [6] concluded: “Collectively, our data demonstrate widespread utility of melanopic illuminance as a metric for predicting the circadian impact of environmental illumination.”

Table I.

Overview of studies on lighting conditions with increased melanopic stimulation (typically by means of a higher CCT) within office settings. Data are extracted from the references as cited in the Table.

Study[A]	Sample size	Test setting	Light conditions	Illuminance (lx, hor.)	Duration[B]	Sleep[C]	Sleepi-ness[C]	Mood / vitality[C]	Perfor-mance[C]	Visual Comfort[C]
Akashi, 2006 [98]	136	Open plan office (cubicles)	3500, 5000 or 6500 K	450 - 850	9 months					–
Baek, 2015 [99]	20	Simulated office	Dark, white, 33% or 66% blue-enriched	40	1 hour				0	
Borisuit, 2015 [100]	25	Simulated office	Daylight vs no daylight	4267 vs. 400	6 hours			(+)[E]		+
De Kort, 2010 [101]	83	Office	Dynamic 300 - 4700 K vs 3000 K	500 - 700 vs 500	3 weeks	0		0	–	
Figueiro, 2017 [13]	109	Office	Daily kight exposure measured	n.a.	7 days	+		+		
Geerdink, 2017 [47]	16	Simulated office	5400 vs 2700 K	1900 vs 130 (vert.)	1 day	+	+		+	
Górnicka, 2008 [102]	12	Simulated office	17000 vs 2700 K	760	1 day		0		0	0
Hoffmann, 2008 [103]	11	Simulated office	Dynamic 6500 vs static 4000 K	500 - 1800 vs 500	3 days			(+)[F]		
Hubalek, 2010 [104]	22	Office/home	Daily light exposure measured	n.a.	7 days	+				
Iskra-Golec, 2012 [105]	30	Open plan office	17000 vs 4000 K	500	3 weeks		–	0		–
Islam, 2015 [106]	40	Simulated office	600 vs 4000 K	300 or 500	0.5 hour					0 (300 lx) - (500 lx)
Mills, 2007 [107]	69	Office (shiftwork)	17000 vs 2900 K	311 vs 354	3 months		(+)[D]	0/+	+	
Smolders, 2017 [108]	39	Simulated office	6000 vs 2700 K	500	1.5 hour		0	–	(–)[G]	–
Vetter, 2011 [109]	54	Office	6500 vs 4000 K	1066 vs 987	5 weeks	+				
Viola, 2008 [49	94	Office	17000 vs 4000 K	310 vs 421	4 weeks	+	+	+	+	+[H]
Wei, 2014 [110]	26	Office (private / open plan)	3500 vs 5000 K	2330 or 3000 lm	2 weeks				–	–

A First author, year of publication, Reference;
B Duration of a single condition;
C +: significant positive effect of higher CCT,
0: no significant effect,
-: significant negative effect;
D Not significant after correction for cluster randomization;
E Only @ 16:00 h;
F Self-rated activity increased and fatigue and deactivation decreased in first 2 days;
G Only at some times of the day;
H For eye strain.

In addition to the office studies, various studies have found a positive correlation between the average daytime light exposure (typically in the range of 50–1000 lx) and the quality and timing of subsequent sleep exists, as referred in the scientific proof points below. Recently it has been demonstrated that optimized office lighting advances melatonin phase and peripheral heat loss prior to bedtime [111].

Scientific proof points of the positive correlation between average daytime light exposure and the quality and timing of subsequent sleep

* Extra light during a workday can improve subsequent sleep (sleep efficiency) [47].
* A relation between earlier sleep timing and more daytime light exposure was found with objective actigraphy and subjective field measurements [112].
* The quality and architecture of sleep is associated with preceding light exposure [18, 67].
* Sleep quality was found to considerably reduced when individuals had low exposure to daylight in subjective reports of sleep in non-interventional studies [66].
* Self-reported sleep quality correlated positively with measured light exposure during the day [104].
* Participants who were exposed to more 'circadian active' light in the morning reported better sleep quality (measured with PSQI) and lower sleep onset latency [13].

As an overall conclusion to this section, there is an expert-scientific consensus that the existing data strongly support the use of melanopic equivalent daylight illuminance in recommendations on light exposures that are beneficial for human health. This can inform current and future lighting designs: the CIE and various groups of experts on circadian and neurophysiological effects of light and the related photometry are endorsing the use of melanopic EDI in their recommendations on lighting to better support human health [6, 12, 113].

4 Two new light quality parameters: melanopic EDI and melanopic DER

Melanopic lighting: A lighting solution designed to activate the melanopsin-containing retinal photoreceptors (the intrinsically-photosensitive retinal ganglion cells, abbreviated to ipRGCs) that mediate the non-visual effects of light on our biorhythm, mood and brain regions involved in learning.

In December 2018 the CIE published an international standard [39] to quantify the ability of a lighting system to activate the melanopsin-based (i.e. melanopic) photoreception of ipRGCs. The CIE standard introduces two new parameters that can be used to objectively characterize effects related to melanopic light exposure:

1. melanopic EDI or melanopic equivalent daylight illuminance
2. melanopic DER or melanopic daylight efficacy ratio

The CIE has recently published an open-access α-opic toolbox that calculates the above quantities based on either a measured (user-defined) spectrum or selected illuminants built into the toolbox [114].

Melanopic light

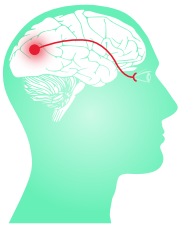
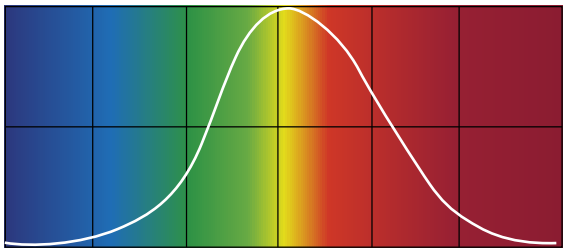
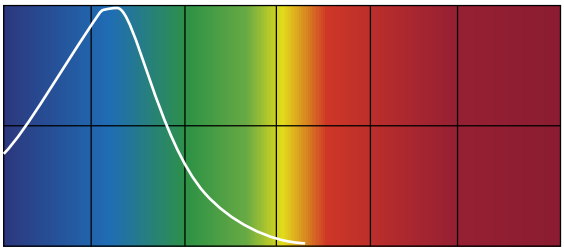
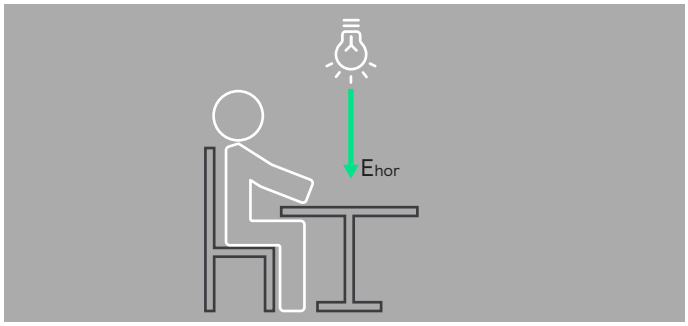
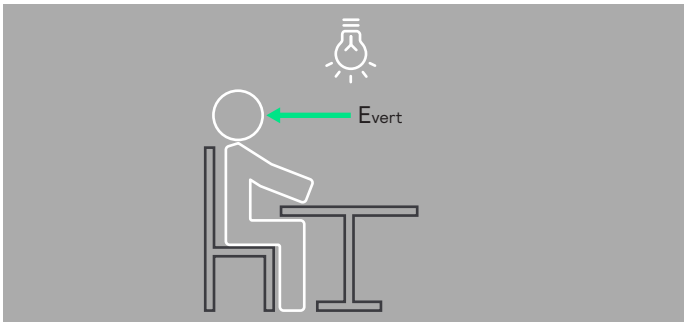
Melanopic light is defined as light that is spectrally weighted with the spectral sensitivity function of the melanopic (i.e. melanopsin-based) photoreceptor, the ipRGC (see Fig. 4). This weighting is done in a similar manner as the photopic-weighting (i.e. by means of the spectral luminous efficiency function for photopic vision) that is used to describe light in terms of lumen and lx [39, 73]. Table II shows a brief overview of the main differences between the important visual and the non-visual quantities used to describe (electrical) light. The non-visual-pathway related quantities (melanopic EDI and melanopic DER) are placed next to some typical visual-pathway related quantities: the colour rendering index (CRI) and the illuminance, with the purpose of demonstrating the main differences and similarities between the non-visual and visual pathways.

Melanopic-EDI

The melanopic equivalent daylight (D65) illuminance (melanopic EDI) is a quantity that expresses the amount of melanopic light. It is defined in international standard CIE S 026:2018 [39]. It expresses the melanopic activation of a particular test light in terms of the amount of lx of daylight D65, an official CIE illuminant [72] used to describe 'average' daylight with a CCT of about 6500K, that generates the same melanopic stimulus strength as the test light. For instance, a melanopic EDI of 30 lx denotes that the test light condition has the same melanopic activation as 30 lx of daylight D65.

Table II.

A brief overview of the main differences between some important visual and the non-visual quantities used to describe (electrical) light. The non-visual-pathway related quantities (melanopic EDI and melanopic DER) are placed next to some typical visual-pathway related quantities: the colour rendering index (CRI) and the illuminance, with the purpose to demonstrate the main differences and similarities between the visual (left) and non-visual pathway (right).

Parameters to characterize the visual function of light	Parameters to characterize the non-visual function of light
Visual pathway 	**Non-visual pathway** 
Relevant photosensitivity: Under photopic conditions visual photoreception is determined by the combination of the signals from the short-, medium- and long-wavelength sensitive cones, with their spectral sensitivity peaks around 565, 540, and 445 nm, respectively. The photometric units lx and lumen are based on the spectral luminous efficiency function for photopic vision, V(λ), which peaks at 555 nm. 	**Relevant photosensitivity:** In the non-visual pathway, photoreception is usually dominated by the intrinsically-photosensitive retinal ganglion cells (ipRGCs). These photoreceptors have an intrinsic light sensitivity which is based on the photopigment melanopsin, and can combine this sensitivity with extrinsic rod and cone signals. The spectral sensitivity of ipRGCs peaks in the cyan part of the spectrum, at 480 nm. 
A spectral metric: Color rendering index (Ra) A measure (denoted by symbol R_a) that indicates how similar colors of various objects appear under the spectrum of a light source in comparison to the spectrum of a reference illuminant (https://cie.co.at/eilv/222). The maximum value for R_a is 100 and its value decreases with increasing color difference between the light source and the reference illuminant. By definition, a daylight spectrum has an R_a of 100. Most conventional LED-based light sources have R_a< 100, to maximize the energy efficiency. Usually most general indoor lighting applications use light with an R_a of 80 or above.	**Spectral metric: Melanopic daylight efficacy ratio (Melanopic DER)** A measure that indicates to what extent the spectrum of a light source stimulates the melanopic (i.e, melanopsin-based) photoreception of ipRGCs in comparison to a reference source/ spectrum that conforms to standard daylight (D65). By definition, a spectrum/source that conforms to standard daylight (D65) has a melanopic DER of 1. A test light with a melanopic DER of 1.25 or 0.75, has a melanopic activation (per lumen) that is 25% more or less as compared to daylight (D65), respectively.
Photopic illuminance (lx): Luminous flux (i.e the received luminous energy with time) incident on a surface, per unit area of that surface, i.e. amount of light that falls on the task. 	**Melanopic equivalent daylight illluminance (lx) (Melanopic EDI)** Product of amount of light (photopic illuminance) that falls on the eye and melanopic DER.  Melanopic EDI_{vert} [lx] = E_{vert} [lx] * Melanopic DER.

Melanopic-DER

The melanopic daylight efficacy ratio is a dimensionless spectral metric that expresses the melanopic activation of a (test) light source as compared to daylight D65 (at the same photopic illuminance). For instance, a test light with a melanopic DER of 0.75 has 25% less melanopic activation (per lumen) as compared to daylight D65. By definition, the melanopic-DER equals 1 when the test light has the same melanopic activation per lumen as daylight D65. When the test light has a melanopic DER of 1.30 it has a 30% higher melanopic activation (per lumen) as compared to daylight D65. Natural light has a melanopic DER close to 1 during most of the day. However, during dawn and dusk the melanopic DER of natural light can increase to 1.75 [73].

The melanopic-DER equals the melanopic EDI ("M") of a test light divided by its illuminance ("P") [39, 73, 109]. As such it represents a dimensionless "M/P" ratio which is quite similar to the S/P ratio. The later is defined in CIE 2020a [115] as the scotopic luminous output ("S") of a test light divided by its photopic luminous output ("P") .

As discussed in section 3, evidence from a large number of field and laboratory studies demonstrates that the melanopsin-based (i.e. melanopic) photoreception of ipRGCs can account for the spectral sensitivity of non-visual responses to light in a wide range of common light conditions [6, 8, 73, 116]. The melanopic activation (melanopic EDI) of a light condition can be easily derived from its (photopic) illuminance at the eye position:

melanopic EDI = illuminance * melanopic DER (1)

where the melanopic DER represents the spectral characteristic of the used light source.

Figure 6 displays the calculated melanopic DER data of a variety of light sources with different CCTs and from different suppliers. In general, the melanopic DER tends to increase with increasing CCT. However, the figure also demonstrates that at a given CCT a wide variety of melanopic DER can apply, mainly due to the spectral tuning possibilities of modern LED technology. This allows for introducing enhanced biological comfort in a standard light design. The BioUp technology as introduced by Signify is an example of such a dedicated spectral tuning design (the green triangle in Figure 6). The blue dot in Figure 6 indicates the melanopic DER of CIE standard daylight (D65), which by definition equals 1.

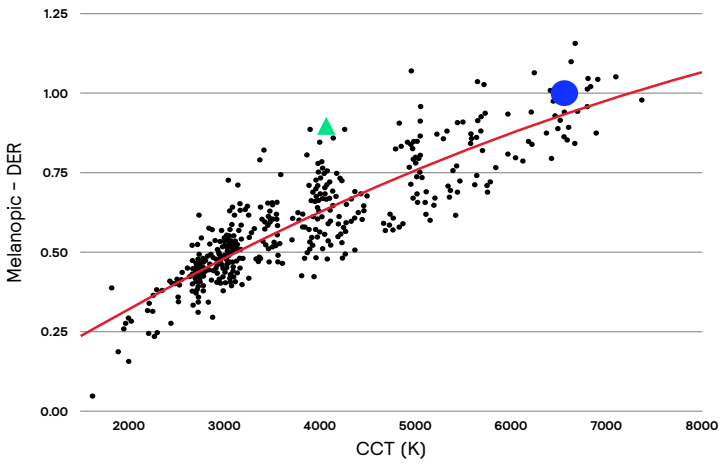


Figure 6: The melanopic DER of a variety of LED sources is plotted against the correlated color temperature (CCT (K)). The blue dot represents the melanopic-DER of the CIE standard daylight (D65) spectrum (melanopic-DER of 1). The green triangle represents a cyan enhanced spectrum at 4000 K (BioUp Signify technology). The melanopic DER is calculated according to CIE S026 [39, 114].

From a lighting design perspective, the illuminance at the eye position and the spectrum of the used light source are two critical parameters to modulate ipRGC activation and ensure appropriate regulation of the biological clock and its circadian rhythm. However, the effectiveness of light to regulate the body clock does not only depend on illuminance and spectral composition of the electrical light but also on other aspects such as exposure duration, prior light history, timing, and dynamics of the light exposure, as well as interindividual differences in sensitivity to light. Particularly elderly people may be less sensitive to short-wavelength radiation due to yellowing of the eye lens. This implies that they require a higher radiation dose to obtain the same ipRGC activation as compared to teenagers.

The following considerations usually apply:

1. timing of light exposure: early morning light advances the body clock (this facilitates an earlier bedtime and sleep onset), evening light delays the body clock (this facilitates a later bedtime and sleep onset) [21].
2. illuminance: higher light levels result in stronger effects (as long as the threshold for saturation is not yet reached, see Fig. 7) [6, 22] .
3. spectrum: effects are stronger when the spectrum has more melanopic content (as long as the threshold for saturation is not yet reached) [6].
4. exposure duration: increasing exposure duration increases effect size (in a non-linear fashion and as long as the threshold for saturation is not yet reached) [23-25].
5. light history: more daytime light exposure can reduce the (sleep-disruptive) impact of evening/nighttime light exposures [26-29].
6. the application context: interindividual differences in light sensitivity are reported to be large [30] and different populations (such as children, seniors, shift workers, healthcare patients) have different lighting needs [31-33].

5 Recommendations for melanopic lighting

For day-active people, a recent CIE position statement [12] advises to have light conditions with a high melanopic EDI during daytime, while low melanopic EDIs are recommended for sleep- and rest-supportive lighting in the evening and at night.

People spend approximately 90% of their time indoors [117]. However, the human indoor environment provides relatively little light during daytime, especially in comparison with natural daylight outdoors [118]. Outdoors the daytime illuminance is typically higher by a factor of 10 up to 500 as compared to indoors. For instance, the European standard for lighting of workplaces [10] specifies minimum values for the maintained horizontal illuminance in offices between 200 lx and 750 lx, depending on the specific task, whereas the horizontal illuminance outdoors can be as high as 150 000 lx [119]. Civil twilight on a semi-overcast day has a maximum (horizontal) illuminance of about 400 lx [9], and as such one could say that an indoor illuminance of 500 lx measured horizontally on a desk surface, as for instance specified in the EU standard for workplaces [10] is rather modest and resembles civil twilight.

Although the importance of daytime light for human health and well-being is well established, our modern indoor living style has profoundly and irreversibly changed our work and social schedules to become much more variable, irregular and disconnected from the biological clock and the natural light-dark cycle. Increasing indoor light exposures during the day towards more outdoor-like exposures to bright natural daylight will be supportive for the non-visual functions of light and thus our circadian and general health.

However, increasing the daytime light output of indoor lighting installations conflicts with the built environment requirements with respect to energy consumption and carbon footprint. A subtle balance between improving people's lives by bringing the power of natural light into offices and creating a better world through delivering the most energy-efficient lighting solutions needs to be established, which raises the question:

What are good melanopic EDI ranges to strive for when illuminating office environments?

At this moment we do not know the precise answer since dose-response relationships for daytime light exposures are not yet fully established. At present there is no hard scientific underpinning on what daytime amount of melanopic light is optimal for office workers' health. However, the established importance of securing sufficient daytime light exposure has fueled the interest in the role of lighting within healthy and sustainable building designs.

The US-based organization IWBI has introduced a building certification program that is called the 'WELL Building Standard' which was one of the first to include some minimal requirements for melanopic lighting in their circadian lighting paragraph [40]: to gain 3 points for circadian lighting design (L03), the electric lighting should provide a melanopic equivalent daylight illuminance on the vertical plane at eye level of the occupant of at least 163 lx.

Next to the minimum requirements within the 'WELL Building Standard', a group of experts in lighting, neurophysiological photometry and sleep and circadian research recently published a paper with consensus-based recommendations for healthy daytime, evening and nighttime light exposure [11]. Figure 7 visualizes the generalized dose-response relationship that describes various biological response (e.g. melatonin suppression, circadian phase shifting and alerting effects) measured after long (>2h) light exposures in the evening and at night to primarily broadband light. The sigmodal relationship between light dose and means that the response remains small up to a certain threshold (~1 lx melanopic EDI), after which it increases with increasing light dose. However, beyond a certain light dose (~250 lx melanopic EDI), the response saturates and no longer increases with increasing light dose. Based on their comprehensive analysis of the sensitivity of human non-visual responses to retinal light exposure (in the evening and at night) they recommended a minimum melanopic EDI of 250 lx at the eye for daytime indoor environments (measured in the vertical plane at ~1.2 m height) [11]. It is expected that this 250 lx melanopic EDI threshold

(which is derived from evening and nighttime light exposures) also helps securing strong non-visual responses during daytime. The potential benefits relate to sound sleep, better daytime functioning & cognition and alleviating stress. This range should normally be avoided during evening and night time. A melanopic EDI ≥ 250 lx is deemed useful to promote optimal physical and mental health and performance. Note that based upon the dose-response curve in Figure 7 recommendations can also be provided for the sleep environment (i.e. melanopic EDI ≤1 lux) and for appropriate evening light (i.e. Melanopic EDI ≤ 10 lx is appropriate for evening use within areas that are intended to be restful and sleep-friendly, lower values may be expected to be more sleep-supportive). This is visualized by the gray shades in figure 7.

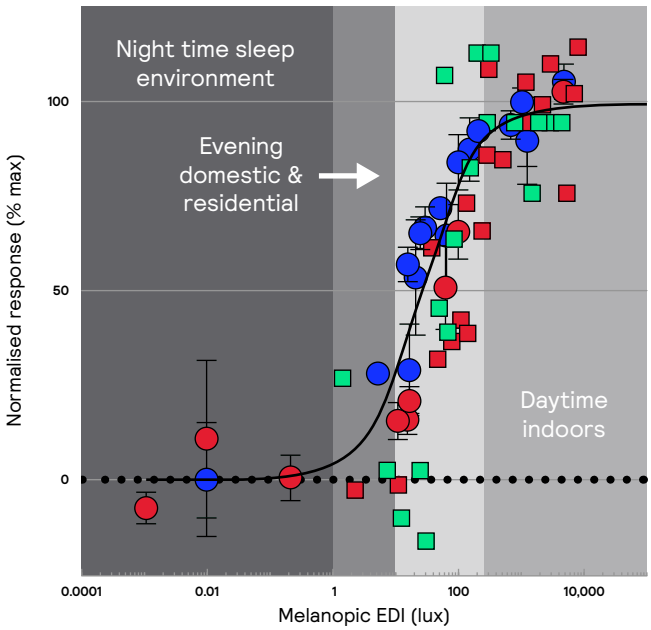


Figure 7: Dose-response relationship describes various biological response (e.g. melatonin suppression, circadian phase shifting and alerting effects), plotted as blue circles, red squares & circles and green squares, respectively, that results after long (>2h) light exposures in the evening and at night to primarily broadband light. Adapted from Ref. 6.

The ≥250 lx threshold for daytime illumination certainly provides a good starting point, but may be insufficient to optimally support health and performance under all conditions. For instance, as earlier mentioned: in their review Xiao et al [93] reported 4 publications [94-97] in which participants felt more alert in the ≥ 1000 lx condition compared to the 100–400 lx condition during the daytime. Assuming a melanopic DER of ~0.6 for a CCT of 4000K, see Figure 6. An illuminance of 1000 lx corresponds to a melanopic EDI of 600 lx. Also a number of scientific field studies have found improvements in sleep and/or performance when the daytime light exposure in the office environment is increased [13, 49, 65, 92]. Therefore, during daytime it can be argued that a higher melanopic EDI is better, although this should not supersede existing guidelines for visual function, comfort and safety.

Another argument for promoting even higher melanopic EDI's is the interindividual sensitivity differences. The sensitivity to light can vary by more than one order of magnitude between individuals as visualized in Figure 8 [30]. The figure highlights two individual dose–response curves: an individual with high light-sensitivity (blue) and an individual with low light-sensitivity (red), the individual curves for all other participants are plotted in gray. Individual data points are shown as crosses. The photopic illuminance in this figure can be converted into a melanopic EDI, i.e. 100 photopic lx corresponds to a melanopic equivalent daylight illuminance of 51.7 lx, and 1000 photopic lx corresponds to a melanopic equivalent daylight illuminance of 517 lx. In order to create healthy indoor illumination for the majority of occupants, recommendations could, for instance, be based on the ambition to secure more than 75% of the maximum response within the population quartile with the lowest light sensitivity.

The WELL accreditation system [40] recommends a melanopic equivalent daylight illuminance of at least 163 lx during daytime to gain certification points, while the data in Figure 8 indicate that, in the least light-sensitive individual (see red line in Figure 8) an illluminance of 350 lx results in about 50 % of the melatonin suppression response [30, 120]. So, for this individual the WELL daytime threshold might be too low.

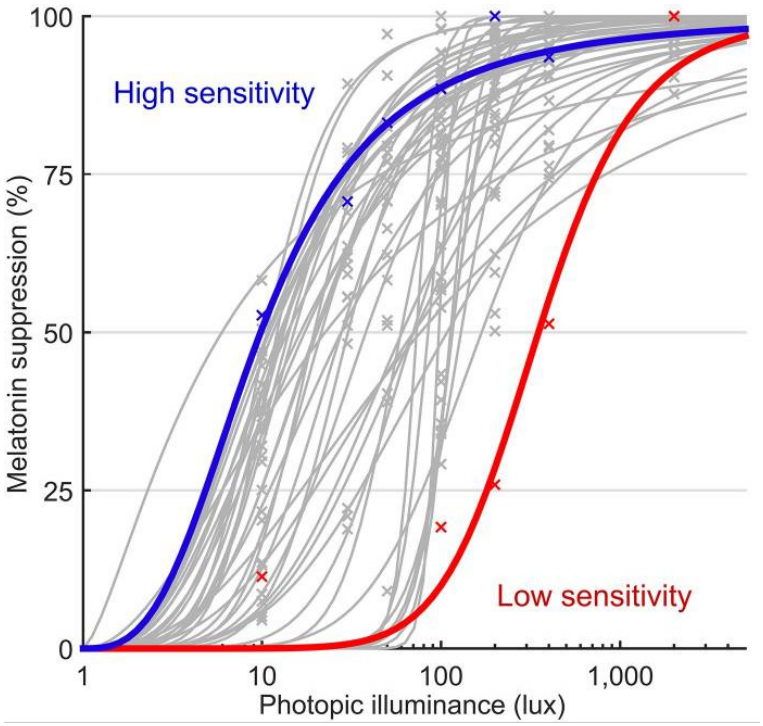


Figure 8: Dose-response relationships for melatonin suppression in 55 individuals after 5h evening light exposure that starts 4 hrs before habitual bedtime and has a CCT of 4100K and a melanopic DER of 0.517 [115]. Adapted from Ref. 30.

Furthermore, the response threshold of the human circadian system can vary with light exposure duration and also depends on the response being investigated e.g. melatonin suppression, subjective or objective alertness, circadian resetting etc. [6]. However, it must be noted that the light sensitivity of non-visual responses during daytime and nighttime might not be identical, research in this domain is ongoing.

Although for healthy indoor light environments a melanopic EDI of at least 250 lx is recommended [11], somewhat lower melanopic light levels may already provide some modest non-visual benefits for instance with respect to a better circadian entrainment (biorhythm support) and a sense of well-being. Potential benefits when applying melanopic lighting in the range 150-250 lx in offices might include improved workplace satisfaction, feeling more energized during the day, an easier wake-up and sound sleep as well as a better connection to time-of-day (for instance by improved circadian alignment and/or 24-hour melanopic light variations within a dynamic lighting solution). Obviously, the potential benefits of the lower melanopic ranges also apply (and possibly even more strongly) for the higher melanopic ranges. It must be mentioned that achieving the above-mentioned benefits is certainly not guaranteed due to the high number of confounding parameters such as interindividual differences in prior light exposure, personal traits and sensitivity to light. Moreover, also sleep behaviour, (outdoor) activities and other social and organizational context factors may strongly influence office workers' general sense of well-being and mask potential non-visual benefits of light. In addition, it is good to realize that different populations (like children, seniors, shift workers, healthcare patients) have different lighting needs [31-33].

6 Concluding

Melanopic light solutions are supportive for a strong and robust body clock due to their ability to specifically target and activate the melanopsin-based photoreception of ipRGCs which powerfully mediate light's non-visual responses [6-8]. A robust body clock is supportive for daytime alertness and performance and reduces the propensity to be awake and functioning at times that our biological clock and physiology is programmed to support sleep. A stronger, more natural and outdoor-like light-dark cycle improves the strength of the 24-hour rhythm of the body clock and its alignment with the behavioral sleep-wake cycle, which is supportive for general health and productivity [34-38]. Based on the insight that light plays a much bigger role than vision only, the CIE has defined two new quantities in an international standard [39] to specify the lighting environment for its ability to support health and well-being aspects: melanopic equivalent daylight illuminance (melanopic EDI) and melanopic daylight efficacy ratio (melanopic DER). These quantities can be used in combination with existing lighting criteria relating to visual function and comfort. A first guideline for daytime lighting can be to maximize melanopic EDI as much as possible, although this should not supersede existing guidelines relating to visual function, comfort and safety.

So far, the existing knowledge on light and its important role for health has not (yet) been translated into requirements or specifications for melanopic lighting that have gone through the full consensus and balloting process required for international standardization in either CIE or ISO.

Next to the minimum requirements within the 'WELL Building Standard', a group of experts in lighting, neurophysiological photometry and sleep and circadian research published a paper with consensus-based recommendations for healthy daytime, evening and nighttime light exposure [11]. Based on their comprehensive analysis of the sensitivity of human non-visual responses to retinal light exposure (in the evening and at night) they recommended a minimum melanopic EDI of 250 lx at the eye for daytime indoor environments (measured in the vertical plane at ~1.2 m height). A melanopic EDI > 250 lx is deemed useful to support and promote optimal physical and mental health and performance. It merits to be noted that achieving all benefits in every context is certainly not guaranteed due to the high number of confounding parameters such as interindividual differences in prior light exposure, personal traits and sensitivity to light. Moreover, also sleep behaviour, (outdoor) activities and other social and organizational context factors may strongly influence office workers' general sense of well-being and can potentially mask non-visual benefits of light. In addition, it must be realized that different populations (like children, seniors, shift workers, healthcare patients) can have different lighting needs [31-33].

Researchers continue to investigate the pathways by which ocular light exposure influences human health and well-being and it needs to be monitored whether the currently specified melanopic recommendations need to be adjusted as new insights become available. However, in the mean time, present melanopic recommendations can facilitate decision making to transform your office space towards better building design to optimally support occupants' comfort, health and well-being.

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