# Integrative Lighting – Paving the Way toward Healthful Light and Lighting

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Light has important functions beyond vision, and these functions are often referred to as non-visual or non-image forming effects/responses of light. They include the regulation of our physiology (hormones), behaviour, mood and circadian rhythms, hence controlling our ability to remain awake and concentrated (for work/learning) or to fall (or remain) asleep. In so called integrative lighting[1] the visual and non-visual effects of light are combined to produce physiological and psychological benefits for human users.

On our planet, the 24h light-dark cycle constitutes an important environment signal that allows many organism to express and adapt their rhythms, physiology and behaviour to the 24-hour variations in our environment. In mammals, the internal 24h rhythm (also referred to as the circadian rhythm, or the body clock) is coordinated by the suprachiasmatic nucleus (SCN) located within the brain in the anterior hypothalamus. The SCN receives light input from intrinsically photosensitive retinal ganglion cells (ipRGCs) that contain the photopigment melanopsin. Under most practically relevant situations, the spectral sensitivity of non-visual responses to light can be well described by the intrinsic, melanopsin-based, spectral sensitivity of ipRGCs[2], which peaks in the short wavelength portion of the visible spectrum around 480-490 nm in humans.[3]

The melanopsin-based photoreceptor (often denoted by the shorthand ipRGC) is known to combine its own melanopsin-mediated (i.e., melanopic) response to light with (extrinsic) signals from rod and cone photoreceptors[3]. In 2018 an internationally-balloted consensus metrology framework has been standardized [4] to assess and characterize light levels based on the degree to which they activate each of the five different ($\alpha$-opic) photoreceptor types (i.e. three kinds of cones, rods and ipRGCs) in the human retina. The framework comprises five $\alpha$-opic irradiances and five $\alpha$-opic Equivalent Daylight Illuminances ($\alpha$-opic EDIs) that have a direct linear relationship with the luminous and/or radiant flux of a light source.[4, 5] The $\alpha$-opic metrology allows to systematically investigate the extent to which a particular circadian, neuroendocrine or neurobehavioral response to light is driven by a single photoreceptor or by a combination of photoreceptors, and whether this depends, for instance, on the amount, duration or timing of the light exposure.[6, 7]

The typical human indoor light environment is quite different from the natural light-dark cycle outdoors, both in terms of spectrum and amount of light exposure. The ubiquitous availability of electric light enables us to spend large parts of our day indoors, in conditions with limited, or sometimes even without, any natural daylight. During daytime we are therefore frequently exposed to light conditions that are relatively dim (with daytime illuminances that frequently do not exceed civil twilight on a semi-overcast day[8]), while the use of electric light during the evening and at nighttime deprives us of natural darkness. Consequently, in our 24/7 society, we are exposed to dimmer days, brighter nights and lower day-night contrasts as compared to the natural light-dark cycle outdoors.[9-11] This has negative consequences for our mental and physical health, sleep and performance.[12-14]

Some examples that highlight the important role of light and circadian rhythms for sleep, mental and physical health are:

- Light at night suppresses the natural secretion of the sleep-supportive hormone melatonin, increases sleep onset latency, increases alertness and impairs cardiometabolomic function [15, 16]

- Light exposure in the early morning (i.e., after waking up) advances the body clock and facilitates an earlier bedtime and sleep onset, while evening light delays the body clock and facilitates a later bedtime and sleep onset. [17]
- Low daytime light levels delay sleep-timing and increase interindividual differences in sleep timing.[9, 18]
- More daytime light exposure can reduce the alerting and sleep-disruptive impact of evening/nighttime light exposures.[19-22]
- Interindividual differences in light sensitivity can be large [23] and different populations (such as children, seniors, shift workers, healthcare patients) have different lighting needs [24-26].
- People with lower 24h light exposures have a later sleep timing [27] and people with diminished daytime light exposures report a lower sleep quality [28-30]
- Evening types report poorer sleep quality and higher levels of work-related fatigue than morning types [31]
- People with a later chronotype (mid sleep timing on free days) and more social jet-lag report more depressive symptoms [32]
- People with more (day)time spent outdoors have lower risk of lifetime depression [13]
- Disruption and misalignment of circadian rhythms may lead to negative effects on mood, sleep and cardiovascular, reproductive, metabolic, reproductive and immune functions. [15, 33, 34]
- Light at night has a negative impact on wild organisms and ecosystem function [35, 36]

Recently an international expert workshop on circadian and neurophysiological photometry published a set of light recommendations to best support human physiology, sleep and wakefulness within indoor settings.[2] As mentioned earlier, the workshop concluded that under most practically relevant situations, the spectral sensitivity of non-visual responses to light can be well described by the intrinsic, melanopsin-based, spectral sensitivity of ipRGCs. The workshop recommendations were therefore expressed in terms of melanopic EDI (measured at the eye position of the user (with a detector orientation that corresponds to the dominant direction of gaze) according to:

- Throughout the daytime the recommended minimum melanopic EDI is 250 lx.
- During the evening, starting at least three hours before bedtime, the recommended maximum melanopic EDI is 10 lx.
- The sleep environment should be as dark as possible with a recommended maximum melanopic EDI of 1 lx and 10 lx in case unavoidable activities during the nighttime require vision.

These recommendations are intended for healthy adults (18-55 yrs) with a day-active schedule, without the intention to supersede existing guidelines and regulations relating to for instance, visual function, comfort and energy consumption. They provide highly needed additional considerations and guidance to successfully accomplish integrative lighting solutions.

In the presentation the above aspects and insights will be discussed in more detail.

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