Implementing non-image-forming effects of light in the built environment

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Implementing non-image-forming effects of light in the built environment: A review on what we need

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ABSTRACT

This paper presents a theoretical framework for incorporating the non-image-forming effects of light into daylighting design in the built environment. The framework includes human performance indicators to measure the magnitude of the non-image-forming effects of light as well as light factors to quantify these effects. In addition, architectural (daylighting) design parameters are included to control the magnitude of the light factors reaching indoor environment. To assess the magnitude of the non-image-forming effects of light in daylighting design process, threshold values for every light factor are discussed. A distinction is made between luminous and temporal characteristics of every light factor and the application of their thresholds in daylighting design process. The proposed framework enables stakeholders in the field of daylighting to incorporate the non-image-forming light requirements in design and to evaluate the potential of indoor spaces with regard to these requirements.

Contents

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1. Introduction

Human beings have evolved under the influence of the dynamic patterns of daylight. Light entering the human eye does not only enable the performance of image-forming (IF) tasks, but also influences the human health and well-being via long-term and short-term (acute) non-image-forming (NIF) effects.

Ocular, or more precisely, retinal exposure to light stimulates three types of photoreceptors: rods, cones, and the melanopsin-containing intrinsically photosensitive Retinal Ganglion Cells (ipRGC). Rods and cones transduce light into neural signals that carry IF information through ganglion cells. These are sent to the thalamus and the visual cortex in the brain where images are being processed.

The ipRGCs constitute a small fraction of the total number of ganglion cells that not only receive the input from rods and cones, but also are intrinsically photosensitive. They convert light into NIF neural signals that are transmitted via retino hypothalamic tract (RHT) to the Supra-Chiasmatic Nuclei (SCN) of the hypothalamus in the brain [1,2]. The SCN, or biological clock, generates and regulates a set of endogenous rhythms of the human body through its connection to the central nervous system. Endogenous biological rhythms can be grouped according to their duration in:

1. Ultradian rhythms (<24 h), e.g., pupillary diameter, REM sleep,
2. Circadian rhythms (24 h), e.g., sleep awake, melatonin, alertness,
3. Infradian rhythms (>24 h), e.g., menstrual,
4. Circannual rhythms (approximately one year), e.g., seasonal changes in hormone secretion.

Rather, in literature the term *circadian* is used either as a broad term which covers all the frequency ranges or to define a major focus. This notion is also adopted in this paper.

Nearly every day the timing of the human biological clock needs to be synchronized with the 24-h light/dark cycle of planet Earth. Disruptions in the entrainment of circadian rhythms with this 24-h light/dark cycle can have negative effects such as poor performance, depression, insomnia, heart diseases, weight gain, and even cancer [3,4]. In addition to the long-term effects, light has short-term (acute) effects, for instance on secretion of melatonin hormone and objective and subjective alertness.

The discovery of the ipRGCs showed that there is a dual role for the human eyes when exposed to light: enabling vision through the IF effects and maintaining health via the NIF effects. A substantial number of people in the Western society spend around 90% of their time indoors [5]. This high percentage stresses the importance of daylighting design as it can positively impact not only the vision, but also the health and well-being of building occupants.

For many years, rods and cones were considered to be the only light-responding receptors in the human eyes. Therefore, lighting standards and recommendations have been developed based on the characteristics of these photoreceptors focusing solely on the human vision. It is well known that health-related NIF effects of light are equally, if not more, important as IF effects. Therefore, it is essential to include their requirements in lighting design recommendations and standards. A start has been made on the inclusion of NIF effects of light in electric-lighting design and research [6–9]. However, no specific attention is paid to daylighting design and its impact on the NIF effects. This inclusion is particularly important as most decisions regarding daylighting design (e.g., window size, window position, and glazing type) are made in an early design stage and are difficult to change at a later stage.

Towards the inclusion of the NIF effects of light in daylighting recommendations, this paper introduces, based on findings published in literature, a theoretical framework (see Fig. 1 for a high level overview). Section 2 describes the structure of the framework. Three aspects included in the framework and the relations between them are investigated. Subsequently, the detailed structure of the framework is specified. Conclusions and recommendations for future research are given in the section 3.

2. Theoretical framework and its variables

Different stakeholders are involved in daylighting design of the built environment which should comply with both IF and NIF effects of light. Local authorities and city planners have profound influence on indoor daylight exposure as they decide on the overall height of buildings, width of streets, and urban design. Architects determine daylighting possibilities through designing the building's skin layer including facade and skylights. Glazing/window companies determine (luminous) characteristics of daylight entering the buildings. Interior designers and/or architects influence internal reflections of daylight via designing the shape and the spectral reflectance of interior walls, ceilings, floors, and furniture. Lighting designers determine the electric-lighting design of spaces with or without taking daylight into account. Lamps and luminaires manufacturers determine the scope for development of electric lighting products from which lighting designers can choose. In this paper, we focus on daylighting design in the built environment thus, the theoretical framework is developed to be used particularly for stakeholders involved/interested in this area.

As shown in Fig. 1 aspects included in this framework are: NIF human performance indicators, NIF light factors and related daylighting design parameters. The first two aspects are derived from reviewing previous literature. Architectural design parameters are added by the authors in order to investigate the influence of daylighting design parameters on NIF light factors and thus NIF effects they have on building's occupants. The relationship between these aspects are investigated, and finally the application of the NIF light parameters in daylighting design process is discussed.

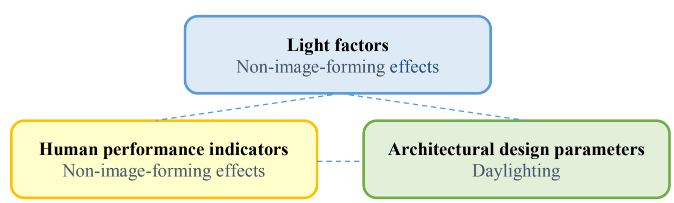

Fig. 1. High level overview of the theoretical framework and its aspects.

2.1. Light factors

The essential light factors necessary for the design of a built environment meeting both the IF and the NIF lighting demands have to be known first. Since the light factors influencing IF effects of light are well-known and the required threshold for each is specified in building norms and standards, in this paper we focus on the light factors stimulating NIF effects.

NIF effects of light and their application in electric-lighting design have been the topic of investigation in different research fields [6,7,9–14]. Rea et al., [6] proposed a first framework for lighting designers and manufacturers in which, in addition to the IF effects, the NIF effects of light were included encompassing five fundamental lighting characteristics: quantity, spectrum, spatial distribution, timing, and duration. In 2003, the CIE has identified five light characteristics that stimulate NIF effects in humans:

intensity (dose), spectrum, timing, duration, and pattern of exposure [7]. As a result, five principles for healthy lighting were determined. In 2004, van Bommel and van den Beld [7] published a broad review on visual (image-forming) and biological (NIF) effects for working spaces. Five health-related lighting quality aspects were studied: lighting level in the eye, spatial distribution, (adaptable) color appearance, timing, and duration. The color appearance included both the spectrum and the correlated color temperature of a light source. Although they did not conclude any threshold for the health-related lighting quality aspects, they identified the abovementioned lighting quality aspects (visual and health-related) that led to the definition of good and healthy lighting. Three years later, Cajochen [9] published a review on acute alerting effects of light. Four light factors were studied: dose or illuminance levels, wavelength, timing, and duration. Recommendations have been made for the implementation of the NIF effects of light to be used in practice for clinical/non-clinical applications and in research. Recently, a modeling framework was proposed by Andersen et al. [15] and Mardaljevic [13] et al. to predict the non-visual (NIF) effects of lighting on building occupants Three illumination criteria were included in this framework: intensity, spectrum, and timing. Thresholds for each illumination criteria were discussed and for 'intensity', the use of a linear ramp-function was proposed.

Summarizing, six factors triggering the NIF light effects have been identified: spectrum, quantity, spatial distribution (directionality), timing, duration, and history. However, not all six mentioned light factors have the same characteristics when daylight is the primary source of lighting. Therefore, in our proposed framework the NIF light factors are grouped in two categories of luminous and temporal, as shown in Fig. 2.

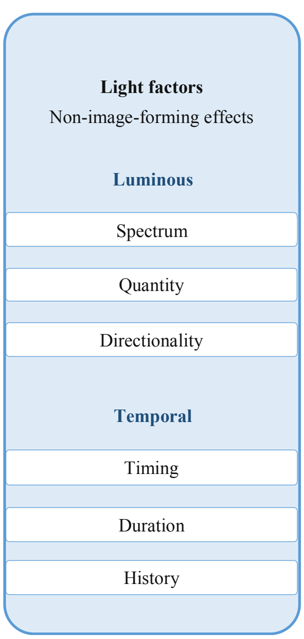

Fig. 2. Two categories of NIF light factors: luminous and temporal.

Spectrum, quantity, and directionality determine the distinct luminous characteristics of daylight. Knowing these light factors one can replicate the luminous distribution. The other three light factors, timing, duration, and history, are temporal characteristics of daylight. These factors depend mostly on building's occupancy pattern and it varies from one person to another. In the following section, based on previous literature, the NIF human performance indicators are identified and the relationship between every light factor and the human performance indicators is studied.

2.2. Human performance indicators related to NIF light factors

In laboratory experiments, the magnitude of the NIF effects of light in humans has been evaluated with the help of different biomarkers of the circadian system or human performance indicators such as melatonin suppression at night (blood sample), objective alertness (e.g., via Electroencephalography (EEG), and Slow Eye Movements (SEMS)), subjective alertness (e.g., via Karolinska Sleepiness Scale (KSS)), cognitive functions, electric response of retina, heart rate, and core body temperature (CBT). Depending on the type of NIF effect, short or long-term, either the level or the cycle of the chosen performance indicator has been studied, as shown in Fig. 3. In the following sub-sections, based on previous literature, the NIF human performance indicators related to every NIF light factor are studied. It should be noted that studies in which wide ranges of the light factors were tested are included. Comparative studies are discussed only when there was no large scale study available.

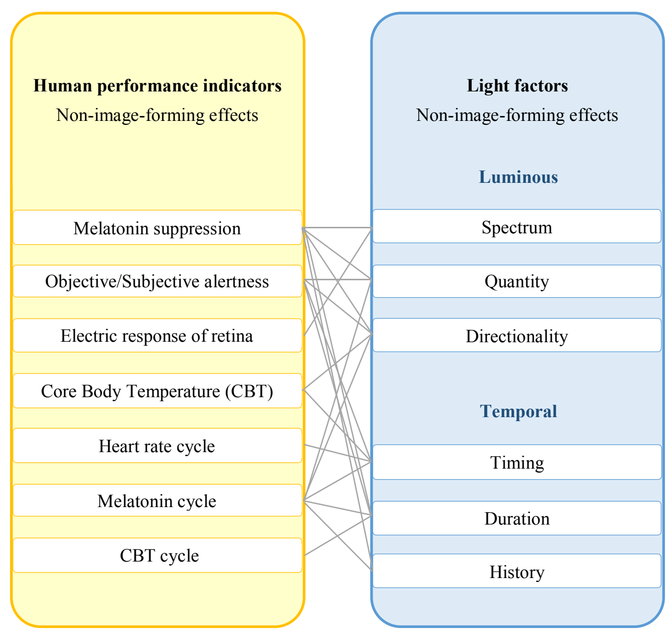

Fig. 3. NIF light factors (dependent variables) in the built environment and human performance indicators (independent variables) including (potential) relationships.

2.2.1. Spectrum

The spectral sensitivity of the human eye varies depending on the wavelength. The spectral sensitivity of the rods and cones has been assessed and published by the CIE. These curves, which are referred to as $V(\lambda)$ and $V'(\lambda)$, demonstrate the relative spectral sensitivity of the photopic (cone-based) and the scotopic (rod-based) vision as a function of wavelengths peaking at 555 nm and 507 nm respectively [16].

The interaction between the ipRGCs, rods, and cones photoreceptors in stimulation of NIF effects is still unknown. According to [17] cone photoreceptors contribute to the NIF process especially in the beginning of the light exposure, and their contribution decreases during the length of the exposure. The spectral sensitivity of the ipRGCs is different from the sensitivity for the photopic/

scotopic vision [18–21]. Although the spectral sensitivity is required to evaluate the NIF efficiency of a light source, the exact spectral sensitivity action spectrum of ipRGCs is not standardized yet. The spectral sensitivity of the ipRGCs is currently determined via either indirect measurements (*in vivo*) using a biomarker (NIF human's performance indicator) in controlled laboratory experiments with human subjects, or via direct measurements (*in vitro*) using the ipRGC's photopigment melanopsin.

Brainard et al. [19] and Thapan et al. [21] published action spectra for melatonin suppression as a biomarker for circadian regulation representing NIF effects of light. Both experiments were conducted during night time when melatonin level in the blood is the highest. Despite the differences in methods and duration of the experimental light used in the two pioneering studies, the findings were fairly similar. Both studies proposed a short-wavelength shifted action spectrum for melatonin suppression with the best curve fits to different opsin templates peaking respectively at $\lambda_{max} = 464$ nm, $R^2 = 0.91$ [19] and $\lambda_{max} = 459$ nm, $R^2 = 0.74$ [21]. Although melatonin suppression is the most commonly used biomarker of circadian regulation in experiments, Hankins & Lucas [20] used the electric response of retina cells. The authors reported an opsin approximated action spectrum for ipRGCs peaking at $\lambda = 483$ nm.

Experiments *in vitro* presented a different action spectrum for melanopsin, the ipRGC photopigment, peaking at around $\lambda = 479$ nm [22]. In Bails and Lucas' experiment [22], the relative sensitivity of melanopsin to eight wavelengths across the visible spectrum was measured and best fitted with an opsin template function with λ_{max} around 479 nm. It is worth noting that monochromatic light sources were used in the aforementioned experiments.

In addition to the aforementioned template functions, different mathematical models were defined to determine the spectral sensitivity of melatonin suppression as a biomarker for circadian regulation and thus NIF effects of light [23–26]. In 2002, Gall and Lapuente [23] defined a simple action function, called C(λ), using empirical data from the Brainard and Thapan studies [19,21]. In their proposed function with λ_{max} of 450 nm, the discontinuity in the spectral sensitivities between 470 and 530 nm observed by Brainard and Thapan is not taken into account. This discontinuity was included in the non-linear model of Rea et al. [24]. Based on Gall's model, Kozakov et al. [26] proposed a nonlinear Gaussian function for circadian action spectrum as well. Fig. 4 shows the empirical data from the *in vivo* and *in vitro* studies, in addition to the circadian action function C(λ) and the relative spectral sensitivity of the photopic vision, called V(λ).

In order to evaluate the NIF efficiency of a light source, not only the spectral sensitivity of the relevant photoreceptor is required but also the Spectral Power Distribution (SPD) of the illuminant. Unfortunately, the SPD of the used light sources in the literature is not always well documented. The SPD of different illuminants is taken into account and compared in Refs. [27,28].

2.2.2. *Quantity*

A sufficient amount (quantity) of light, in the eye, is required for the stimulation of NIF responses in humans. Electromagnetic radiation can be measured either in radiometric and photon quantities for wavelengths between 0.01 and 1000 µm, i.e., irradiance, effective irradiance, or in photometric quantities for wavelengths between $\lambda = 380$ and 780 nm, i.e., illuminance, when the human eye sensitivity is taken into account. Recently, an effort has been made to define new terms relating photometric quantities to photobiological/photochemical quantities [29]. Using the proposed approach, effective irradiance with respect to e.g., C(λ) curve (spectral sensitivity of the melatonin suppression) is the value to measure instead of illuminance. It is essential to make a distinction between photometric quantities and effective irradiance when the NIF effects of light are concerned. Although the term 'intensity' is often used in literature [30–36], illuminance (E) is the value regularly measured and reported which is not a correct value. In order to relate the illuminance to e.g., the effective irradiance with respect to C(λ), one requires vertical retinal light exposure, in addition to the SPD of the illuminant. Unfortunately, these criteria are usually not provided. This lack of information is a barrier to a complete comparative research. A new method of recording/quantifying light proposed by Lucas et al. [2] can prevent this problem by measuring and calculating corneal effective irradiance with respect to rods, cones, and the ipRGC photoreceptors separately. Table 1 gives a brief description of the relevant terminology.

The target human performance indicators to evaluate the effect of the quantity of light on NIF responses in humans are objective and subjective alertness in addition to the melatonin suppression at night. Despite the differences in the time of the experiments (daytime vs. nighttime), all reviewed studies agree on the positive impact of bright light (Evertical > 1000–10000 lx) over dim light (Evertical < 3–200 lx) on subjective and objective alertness [28–31,33,34].

The acute effect of nighttime light exposure on melatonin suppression was investigated by McIntyre et al. [30] using five

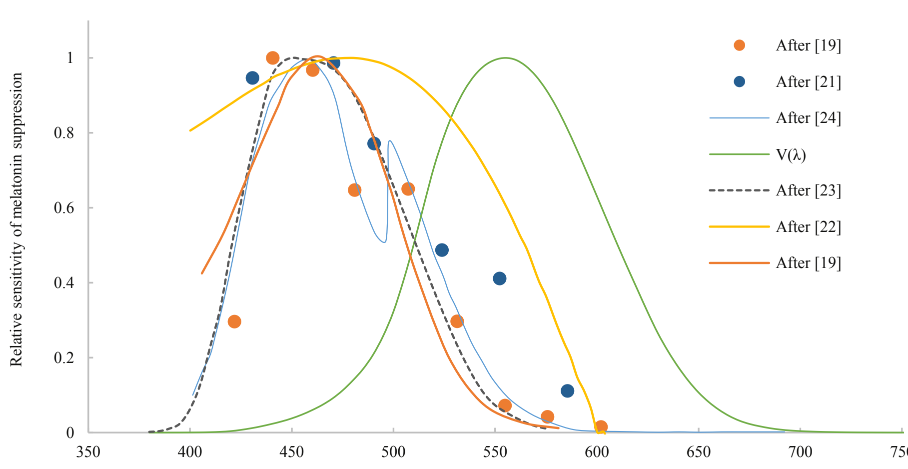

Fig. 4. Overview of relative spectral sensitivity of melatonin suppression C(λ), according to different references, as well as the photopic spectral sensitivity curve of human eye V(λ).

Table 1
Mathematical definition for irradiance, effective irradiance, photon irradiance, and illuminance.

Quantity	Definition	Unit	Mathematical definition	Description	
Irradiance	Power of electromagnetic radiation per unit area on a surface	W m^{-2}	$E_e = \int_0^{\infty} E_{e,\lambda}(\lambda)\, d\lambda$	λ $E_{e\lambda}$	is the wavelength; is the spectral irradiance.
Effective irradiance (with respect to the effect X)	Irradiance weighted for a spectral sensitivity function X	W m^{-2}	$E_{e,x} = \int_0^{\infty} E_{e,\lambda}(\lambda)\cdot X(\lambda)\, d\lambda$	λ $E_{e\lambda}$ $X(\lambda)$	is the wavelength; is the spectral irradiance, is the spectral sensitivity function of the effect X.
Photon irradiance	Number of photons per time per unit area	s^{-1} m^{-2}	$\dot{E}_p = \frac{d\Phi_p}{dA_2}$	$\dot{\Phi}_p$ A_2	is the photon flux; is the receiving area.
Illuminance	Luminous flux incident per unit area	lx	$E = K_m \int_{380\ nm}^{780\ nm} E_{e,\lambda}(\lambda)\ \cdot V(\lambda)\, d\lambda$	λ $E_{e\lambda}$ K_m $V(\lambda)$	is the wavelength; is the spectral irradiance; is the maximum value of the spectral luminous efficacy (683 lm $\cdot$W^{-1}); is the CIE spectral Luminous efficiency function for photopic vision.

illuminance levels. It appeared that light stimuli of 1000 lx suppressed the melatonin level nearly to its daytime level. The acute and circadian effects of nighttime ocular exposure with a wide range of illuminance values, from 3 to 9100 lx on melatonin suppression and phase-shift has been studied by Zeitzer et al. [34]. Findings showed that both outcomes have a non-linear relationship with the illuminance level. These relationships were defined using dose-response curves. According to the dose-response curves, the maximal melatonin suppression and phase-shift occur at ~200 lx and ~500 lx respectively. Moreover, depending on the illuminance values, the magnitude of the phase-shift varies between −1.8 h and −3.2 h. Cajochen et al. [28] performed an experiment similar to the Zeitzer-study for subjective and objective alertness, and defined dose-response curves for each performance indicator. Data from every experiment was fitted to a logistic model. Fig. 5 shows the dose-response relationships between illuminance and melatonin suppression and subjective alertness.

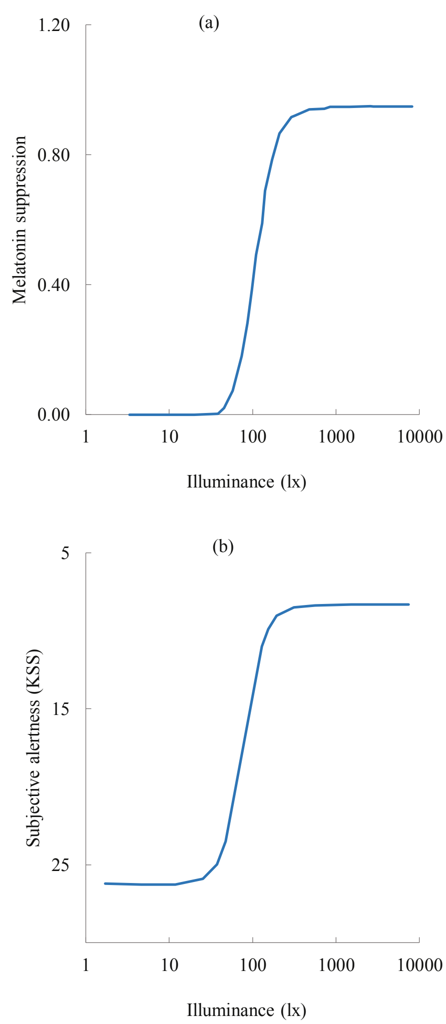

Fig. 5. Doze-response relationship between illuminance and (a) melatonin suppression after [36], and (b) subjective alertness after [30].

2.2.3. Directionality

According to a limited amount of studies the direction of light entering the human eye plays an important role in the magnitude of the NIF effects [37–40]. Four different areas in the human retina have been investigated: inferior (upper visual field), superior (lower visual field), nasal (visual field on the nose side), and temporal retina (visual field on the ear side). It should be noted that these areas are rough indications of subdivisions in the subject's visual field. Melatonin suppression at night, subjective alertness, and CBT are the performance indicators often used when directionality of light is investigated.

Lasko et al. [38] compared the effect of 500 lx illuminance to the inferior and the superior retina with 5 lx illumination to full retina (control condition) in suppressing melatonin. In this study, the light source was simply placed 23° above or below the gaze view line to distinguish the inferior and superior light exposure. Moreover, subjects were asked to watch entertainment videos from a television screen which was placed on the gaze view. Findings showed that after 2 h of exposure to experimental light the (relative) melatonin level was significantly suppressed compared to when the inferior retina was illuminated (~75%). No statistical significance was reached with illumination of the superior retina. Glickman et al. [37] studied the effect of ocular 100 lx and 200 lx illuminance with equal photon dosage under four conditions: full retina exposure (100 lx or 200 lx), inferior retina (200 lx), superior retina (200 lx), and dark control condition. Their results showed that full retinal exposure of both 100 lx and 200 lx and inferior retinal exposure of 200 lx were significantly more effective in suppressing melatonin compared to the superior retina exposure of 200 lx. In contradiction to the Lasko-study [38], in the Glickman-experiment [37] the subject's pupils were dilated and partial retina exposures were controlled for.

Visser et al. [40] investigated the effect of 500 lx light exposure on the four different retinal areas. Although the melatonin level was suppressed from the beginning of the light exposure, the maximum effect was observed at the end of the 2 h exposure. Data revealed that melatonin is significantly suppressed when light illuminates the nasal part of the retina compared to the temporal one. No significant difference was found between superior and inferior illumination. Immediate effects of 100 lx exposure of light to the nasal and temporal retinal areas on melatonin suppression and phase-shift, subjective alertness, and CBT have been studied by Rüger et al. [39]. Findings showed a significant difference in melatonin phase-shift for the nasal retina exposure compared to the temporal retina at the end of the 4 h exposure. Although nasal illumination suppressed melatonin more than temporal illumination, the difference did not reach statistical significance. No difference was observed regarding the alertness or CBT measurements.

2.2.4. Timing

The ipRGCs provide time-of-day information to the biological clock and by doing so, entrain a variety of daily cycles of the human body with the 24-h light/dark cycle. When appropriately timed light exposures can enforce the entrainment of circadian rhythms, mistimed light exposure can disrupt entrainment and consequently put human well-being and performance in jeopardy.

Phase Response Curves (PRC) are often used to illustrate the relationship between timing of light exposure and phase-shift in circadian rhythms. Depending on the timing of the light exposure, the direction of phase-shift varies. Khalsa et al. [41] studied the phase-shifting effects of light exposure before and after the minimum CBT on melatonin PRC. Findings showed that light stimuli applied prior to the CBT minimum delays the phase up to −3.6 h, whereas light exposure after the minimum advances the phase up to +2 h.

In addition to the circadian effects, the acute effects of light exposure on different times of the day have been investigated. Rüger et al. [42] compared the acute effects of day-time versus nighttime light exposure ($E_{vertical} = 5000$ lx) using light therapy devices on heart rate, subjective alertness, fatigue, and CBT. Heart rate and CBT appeared to be dependent on the time of the light exposure as the light stimuli increased these markers only during night time. The subjective alertness and fatigue score were both enhanced independent of the exposure time.

2.2.5. Duration

The efficacy of the NIF effects of light in humans is influenced by the duration (and sequence) of light exposure [43–45]. The target performance indicators to evaluate the effect of the light duration on human NIF responses are melatonin level, CBT and subjective alertness cycles.

The effect of a continuous (5 h) and two different configurations of intermittent light exposure (either ~ 4 × 46 min or 13 × 5.3 min) of $E_{vertical} = 9500$ lx on CBT phase-shift has been investigated [45]. The findings were compared with the results reported in a previous study from the same research group [46]. Although the total exposure in the intermittent conditions was shorter than that of continuous condition, they elicited almost equal phase advance responses. In a similar experiment [44], the effects of continuous (6.5 h) versus intermittent (6 × 15 min) ocular exposure to 9100 lx on melatonin and CBT cycles have been investigated. They have found a comparable phase delay effects despite the duration/sequence of the light exposure. In a follow up study, acute and circadian effects of five different durations of ocular light exposure of 10000 lx, ranging from 0.2 h to 4.5 h, on the melatonin cycle, melatonin suppression, and subjective alertness have been investigated [43]. To broaden the light duration scope, the data from the Gronfier-study [44] for the 6.5 h light exposure were included. Findings showed that melatonin cycle, melatonin suppression, and subjective alertness were dependent on the duration of the light exposure in a dose-dependent manner. The awaking time and its interaction with the duration of light exposure appeared to play a significant role in the magnitude of the subjective alertness.

The effect of duration and quantity of light on melatonin cycle has been compared [47]. Results show that increasing duration of the light exposure (1, 2, and 3 h) increased the magnitude of phase delay of melatonin cycle, whereas increasing the intensity of the light exposure (2000, 3000, 8000 lx) did not change the magnitude of phase delays. In overall, the efficacy of the NIF effects in humans increases with increasing duration [43,45,47] and the sequence [44,45] of the light exposure. When the maximum effect is reached, the magnitude of NIF effects stays constant for longer durations of light exposure [47].

2.2.6. History

The importance of light exposure prior to the experimental light exposure is often neglected in experiments. So far, only little attention has been paid to studying the effect of light history on stimulation of NIF effects. Melatonin suppression and cycle are used as the human performance indicator in experiments. Hebert et al. [48] studied the effect of one week prior dim (15 lx) versus bright (at least 4 h of daylight or bright light of 5000–7000 lx from light boxes) light exposure on melatonin suppression at night. A statistically significant increase in melatonin suppression was observed following the dim light week compare to the bright light week. Smith et al. [49] investigated the adaptation mechanism of human melatonin suppression to prior light history. In a laboratory setting subjects were exposed to either 0.5 lx or 200 lx vertical illuminance for three days prior to the experiment light. Findings showed that melatonin level was significantly more suppressed within the group with dimmed light history compared to bright light history. The impact of three days prior dim light (1 lx) versus semi-typical indoor light (90 lx) on melatonin suppression and phase-shift have been compared [50]. The results show that dim light history was more effective compared to the typical room light on melatonin suppression and phase-shift.

Although the amount of research on this light factor is limited, outcomes from existing research show a similar trend. Findings on the effect of light history can be used to explain the significant effect of intermittent light compared to continuous light if the dim light conditions (<1 lx) in between bright exposures to light (9100 lx) are seen as a small scaled history. Therefore, there is a need to clearly define history (e.g., at least three days before the experimental light exposure) in order to avoid mixing up this light factor with duration.

2.3. Architectural design parameters (daylighting) related to NIF light factors

The characteristics of daylight reaching the human eye inside buildings influences the magnitude of IF and NIF responses in building's occupants. Architects determine daylighting possibilities and thus luminous characteristics of daylight through designing the building's envelope, material properties of the interior walls, floors, ceilings as well as furniture and furnishing, see Fig. 6. In addition to the building related design parameters, there are two environmental design parameters that play a role in NIF effects of light: orientation and exterior ground characteristics [51].

Modification of most daylighting design parameters requires drastic changes and demolition, thus it is important for building designers to consider relations between daylighting design parameters and NIF light factors in early design phase to achieve a

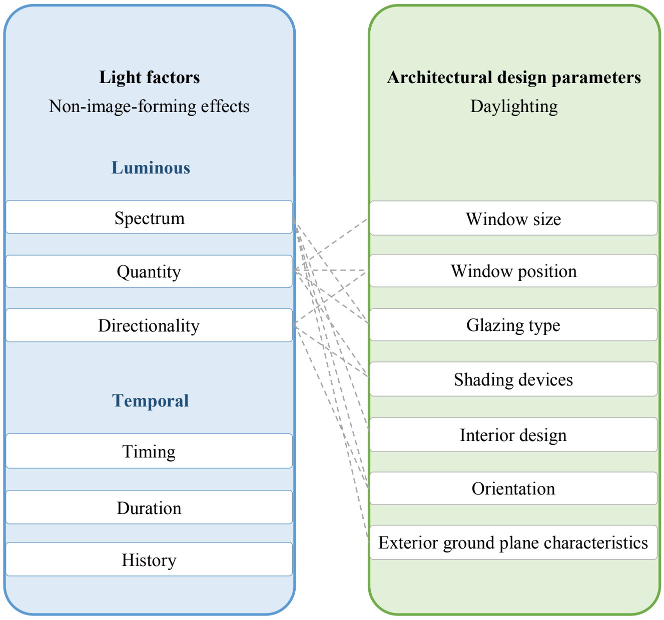

Fig. 6. Two categories of NIF light factors; luminous and temporal, including potential relationships between the design parameters (independent variables) and light factors (dependent variables) in a built environment.

climate that matches the NIF effects requirements. In order to assess the NIF effects of light in daylighting design processes, one needs to know an appropriate threshold for every light factor. However, one should bear in mind that the application of these thresholds differs depending on the characteristic of the light factor (luminous or temporal). Not all six mentioned light factors are equally relevant to architectural design when daylight is the primary source of lighting.

In case of temporal light factors, thresholds can be used to determine a behavior/occupancy profile that supports the NIF requirements of daylight. This occupancy profile will be an outcome of the temporal light factors' thresholds. Such a behavioral profile will be specific for every occupant and varies from one person to another. The current occupant profiles that have been defined based on the standards and have been used (mostly) in the field of building's energy performance, can be replaced with a set of NIF supported occupancy profiles that can be used in the field of daylighting as well. The NIF supported occupancy profiles can help building's occupant to enhance their health by being in their workplace at a certain time of a day for certain duration. Such occupancy profile should be extended to the night time to take into account the effect of history of light exposure.

In case of luminous light factors, thresholds can be used by building designers to choose appropriate daylighting design parameters such that NIF daylight requirements are met. Unlike the temporal light factors, quality of the luminous light factors reaching indoor environment depends on daylighting design parameters. These factors can be controlled/adjusted via design parameters such as glazing type, daylight opening (vertical e.g., windows or horizontal e.g., skylights) size and position. Since the proposed framework in this paper is developed for stakeholders involved in daylighting design, the focus will be on the luminous light factors. Therefore, for every luminous light factor available threshold value(s) and their application in daylighting design are discussed in this section.

2.3.1. Spectrum

In order to measure the NIF spectral efficiency of an illuminant and to translate the photopic values from literature into equivalent values, the spectral sensitivity function of the ipRGCs, the interaction among all three types of photoreceptors, and the SPD of the illuminant need to be known. Using melatonin suppression as a human performance indicator, the *in vivo* and *in vitro* studies have suggested action spectra with peak sensitivities between 460 and 480 nm. Although the *in vitro* studies are more recent, the *in situ* studies by Brainard [19] and Thapan [21] are the only studies on human subjects with a large sample size (n = 77 and n = 22). It can be argued that for *in vitro* situations all the impacts from external factors were excluded. Thus, the results might be less applicable for human beings in real situations. Moreover, it should be noted that there is an evidence for a substantial contribution of cone photoreceptors [17] (and perhaps rods) on stimulation of the NIF responses. The exact interaction of the involved photoreceptors is not known yet. Until then, the spectral sensitivity function for melatonin suppression, derived from the Brainard and Thapan studies, called C(λ) can be used as the representative of the NIF response action spectrum.

Daylight is dynamic. It covers a wide range of spectrum and is rich in blue part which makes it a suitable light source for stimulation of the NIF effects. The spectrum of daylight depends on the time of year and day, the geographic location, the meteorological situation, pollutants, and particular scenery. In daylighting design, the glazing type and interior design such as the spectral reflectance of room surfaces [52] as well as exterior ground plane characteristics, and orientation are the design parameters that impact the spectrum of daylight reaching the building's occupants.

2.3.2. Quantity

Regardless of the time of the experiment (daytime or nighttime), the differences in light levels corresponding to bright and dim light exposures, and the type of light source used in experiments, all studies [30–33,35,36] reported a positive impact of bright light over dim light on the human performance indicators. Taking wide range of illuminance values into account, several dose-response curves have been defined [30,32,36], see Fig. 5 for two examples. With the help of these dose-response curves a non-linear relationship between the amount of light (illuminance) and (acute) NIF effects of light is studied, using melatonin suppression, melatonin phase-shift, or objective and subjective alertness as human performance indicators.

These dose-response curves can be used to determine threshold values for the studied performance indicators. In Ref. [30] thresholds for the half maximal effects are reported (KSS ~ 100 lx, SEMS ~ 180 lx, EEG ~ 90 lx) whereas, in Ref. [36] thresholds for the maximal effects are stated (melatonin suppression ~ 200 lx, melatonin phase-shift ~ 500 lx). These thresholds emphasize the large influence of the typical room light exposure, during nighttime, on activation/triggering (of) NIF effects. In addition to the acute effects, the circadian effects of different light levels on melatonin phase-shift have been studied [36]. The magnitude of the phase-shifts turned out to be dependent on the amount of the light exposure in a non-linear manner. Around 50% of the phase delay achieved by ocular light exposure of 9100 lx occurred in response to ocular light exposure of 106 lx highlighting sensitivity to nighttime light exposure.

Although these dose-response curves give information on the relationship between light quantity and different human performance indicators, they all have been derived from nighttime experiments. In order to use these dose-response curves in daylighting, the possible differences in human sensitivity to light quantity during daytime compared to nighttime should be taken into account. In daylighting design, the quantity of daylight entering the buildings can be controlled by daylight opening

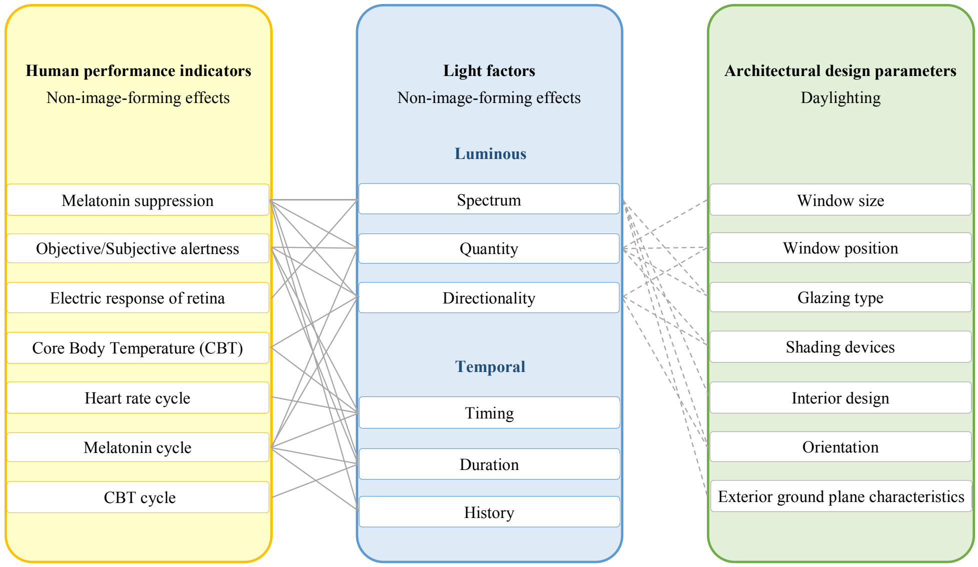

Fig. 7. Theoretical framework including (potential) relations between NIF light factors, NIF human performance indicators, and daylighting design parameters.

(vertical e.g., windows or horizontal e.g., skylights) size and position, glazing type, and shading devices.

2.3.3. Directionality

Directionality of light is an influential parameter in the field of NIF effects and often disregarded in literature. Two areas in the human retina were found to be significantly more effective in suppression of melatonin than others: the inferior and the nasal retina. However, it is not yet known if it is due to the density of the ipRGCs in those areas or their effectiveness. It is worth noting that these results were observed regardless of differences in method (e.g., helmet with shields versus moving light source), light source, and experimental conditions (e.g., 100–200 lx range versus steady 200 lx) in every study [37–40].

Although the number of studies regarding this light factor is limited and there is not always a consent on the most effective areas, it is clear that not all the retinal areas have the same effectiveness when it comes to the NIF effects of light. In daylighting design, this light factor can be influence by design parameters like window position, shading devices and orientation.

2.4. Overall framework

This paper presents a theoretical framework for stakeholders in the field of daylighting design to better understand and impalement the NIF effects of daylight in design of our built environment. The framework as shown in Fig. 7, includes three aspects: NIF human performance indicators, NIF light factors and architectural (daylighting) design parameters. The magnitude of the NIF effects of every light factor have been quantified in literature with the help of the NIF human performance indicators. Based on the input from literature, we identified light factors involved in stimulation of the NIF effects and their related Human performance indicators. In the framework, it is shown which human performance indicator has been used when a light factor was studied.

Moreover, in this paper a distinction is made between luminous and temporal characteristics of the light factors and the application of their thresholds when daylight is the primary source of lighting. Only the luminous light factors appeared to be dependent on daylighting design parameters. That is to say, daylighting design parameters control the magnitude of the luminous light factors inside the building. Subsequently, they dictate the magnitude of the NIF effects of daylight. Potential relations between design parameters and relevant light factors are included. A start has been made to investigate the magnitude of influence of every daylighting design parameter on the NIF light factors [51]. Ongoing research from the authors is devoted to establish the relations among these two aspects. This framework will assist stakeholders in the field of daylighting to better understand the relations between three light factors involved in NIF effects. Moreover, using this framework, one can choose for the most applicable or influential design parameter on the NIF light factors to be included in daylighting design. Tracing back, the influenced NIF human performance indicator can be identified. Reversely, one can choose for the NIF human performance indicator and find the related light factor and daylighting design parameters.

3. Conclusions: what do we need?

The aim during building design, including the daylighting aspects, should be implementing both IF and NIF light requirements without compromising user comfort and energy consumption. A holistic approach to daylighting design would allow increasing the well-being of occupants. In order to facilitate the implementation of NIF effect in daylighting design, we proposed a theoretical framework including three aspects: NIF human performance indicators, NIF light factors, and architectural (daylighting) design parameters. The relations between the NIF human performance indicators and light factors derived from previous literature. Moreover, potential relations between NIF light factors and architectural (daylighting) design parameters were included. Future studies from the authors of this paper will elaborate further on the sensitivity of light factors to these design parameters from which the exact relations between these aspects will be concluded. The proposed framework enables stakeholders in the field of daylighting design to include NIF light requirements in design and to evaluate the potential of a space with regard to NIF effects of daylight.

In order to assess the effects of the NIF light requirements, one needs to know threshold value(s) in the form of dose-response curves relating every light factor to both daytime and nighttime human performance indicators. So far, all suggested threshold value(s) have been derived from (a few) nighttime studies with sleep deprived subjects and their values have not yet been validated. This leaves room for future research. Moreover, attention should be paid to differences in the application of the threshold value(s) depending on the characteristics of the light factors (luminous or temporal). In case of temporal light factors, thresholds can be used to develop an occupancy profile that supports the NIF requirements of daylight. A set of validated behavior/occupancy profiles extended to the night times, is what we need that itself is a distinct research field.

In daylighting design, thresholds for luminous light factors can be used by building designers to choose appropriate daylighting design parameters such that these thresholds are met. It is worth noting that in the design process threshold ranges are more valuable than exact values. For instance, with regard to the quantity of light, instead of a hypothetical threshold of $E_{\text{vertical}} = 1000$ lx, ranges between 800 and 1200 lx is sufficient to decide on e.g., the size of the daylight opening. These ranges can be obtained from the required dose-response curves.

In addition to the independent influence of every light factor on the NIF effects of light, the dependencies (inter-relations) between luminous light factors and temporal ones can be taken into account in future studies. For instance, depending on the personal history of light the threshold for other light factors (e.g., duration, quantity, and timing) might vary; or depending on the time of the day and the quantity of light, the spectral sensitivity of the NIF responses might vary. Taking into account the inter-relations of light factors, dynamic or situation-dependent thresholds can be a practical solution.

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