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Review

Sustainable Architecture and Human Health: A Case for Effective Circadian Daylighting Metrics

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Abstract: The development of the fluorescent lamp and the air-conditioning system resulted in buildings being lit inexpensively without having to rely on daylighting to save energy, as was the case during the incandescent lamp era. Consequently, architects were able to design buildings with deep floor plates for maximum occupancy, placing workstations far away from windows since daylighting was no longer a necessity. Floor-to-ceiling heights became lower to minimize the inhabitable volumes that needed to be cooled or heated. With the rising costs of land in some major American cities such as New York City and Chicago at the beginning of the twentieth century, developers sought to optimize their investments by erecting tall structures, giving rise to densely inhabited city centers with massive street canyons that limit sunlight access in the streets. Today, there is growing awareness in terms of the impact of the built environment on people's health especially in terms of the health benefits of natural light. The fact that buildings, through their shapes and envelope, filter a large amount of daylight, which may impact building occupants' health and well-being, should cause architects and building developers to take this issue seriously. The amount and quality of light we receive daily impacts many of our bodily functions and consequently several aspects of our health and well-being. The human circadian rhythm is entrained by intrinsically photosensitive retinal ganglion cells (ipRGCs) in our eyes that are responsible for non-visual responses due to the presence of a short-wavelength sensitive pigment called melanopsin. The entrainment of the circadian rhythm depends on several factors such as the intensity, wavelength, timing, and duration of light exposure. Recently, this field of research has gained popularity, and several researchers have tried to create metrics to quantify photopic light, which is the standard way of measuring visual light, into a measure of circadian effective lighting. This paper discusses the relationship between different parameters of daylighting and their non-visual effects on the human body. It also summarizes the existing metrics of daylighting, especially those focusing on its effects on the human circadian rhythm and its shortcomings. Finally, it discusses areas of future research that can address these shortcomings and potentially pave the way for a universally acceptable standardized metric.

Keywords: daylighting; circadian rhythm; lighting metrics; daylighting simulations

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1. Introduction

One of the developments in the late nineteenth century with profound implications for building design was the invention of the fluorescent lamp. By the 1930s, the use of this new lamp, particularly in commercial buildings, became widespread because of its improved energy efficiency compared to the earlier incandescent lamp. Around the same period in the late 19th century and early 20th century, Willis Havilland Carrier invented what is known today as the air-conditioning system. The combination of these two technological developments—air-conditioning technology and the fluorescent lamp—allowed developers to erect buildings anywhere, irrespective of climate, while still providing a comfortable indoor environment. The fluorescent lamp, because of its energy efficiency, allowed buildings to be lit inexpensively without having to rely on daylighting to save energy, as was the case during the incandescent lamp era. As a consequence, architects were able to design buildings with deep floor plates for maximum occupancy, placing workstations far away from windows since daylighting was no longer a necessity. Floor-to-ceiling heights became lower to minimize the inhabitable volumes to be cooled or heated. With the rising costs of land in some major American cities such as New York City and Chicago at the beginning of the twentieth century, developers sought to optimize their investments by erecting tall structures, giving rise to densely inhabited city centers with massive street canyons that limit sunlight access in the streets.

The historical watershed event of the 1973 energy crisis led to a sudden paradigm shift related to building energy consumption. Conservation became the issue of the day, and the solar architecture movement was born as a response to such a crisis. Today, there is growing awareness in terms of the impact of the built environment on people's health, especially in terms of the health benefits of natural light. The fact that buildings, through their shapes and envelope, filter a large amount of daylight, which may impact building occupants' health and well-being, should cause architects and building developers to take this issue seriously. Research in this area has been unfortunately insufficient. Nevertheless, evidence points to potential health problems when people are not exposed to adequate levels of daylight. After all, people spend as much as ninety percent of their time indoors [1]. Daylighting, which is the controlled admission of natural light into a building to provide effective internal lighting [2], is therefore crucial for both the physical and mental health outcomes of indoor occupants. However, most research on daylighting has been based on the energy-saving potential [3] and the visual effects of daylighting [4,5]. An important non-visual effect (perceived by our eyes but not related to vision) of daylighting is on the human circadian rhythm that influences various aspects of human health including sleep, cognition, and mood. This is a topic that researchers have only recently begun to pay attention to. Although numerous studies have found evidence linking the circadian impacts of light on sleep [6–9], cognition [10–13], and the mood [14–17] of building occupants, these research findings have not been adequately implemented into applicable design practices that can be easily adopted.

Owing to the dynamic nature of daylight availability (caused due to variations in the position of the sun throughout the day and across seasons, as well as due to changing cloud cover), circadian daylighting design is very challenging as it needs complex computer simulations for reasonably accurate predictions. This has led to a shortage of daylighting design tools that account for the luminous (intensity and spectrum) and temporal (timing and duration) aspects of daylight, the variability of which has been shown to impact the regulation of the circadian rhythm of building occupants. Moreover, there are no standardized metrics for the circadian impacts of daylighting. Therefore, a need exists to explore existing daylighting metrics and investigate their applicability in the regulation of circadian rhythm.

2. Background: Daylighting and Circadian Rhythm

To explore the circadian impact of lighting on building occupants, we must first understand the relationship between light and the human circadian cycle. The circadian rhythm is a roughly 24 h cycle that responds to environmental cues, such as the presence and the absence of light, to regulate various bodily functions such as sleep–wake cycles, hormonal cycles, metabolic activities, and cognition [18]. One of the key non-visual responses of the human body to daylight is the entrainment of our circadian rhythm, which is the synchronization of the internal circadian clock with the external environment [19]. The non-visual photoreceptors in our eyes have a pigment called melanopsin that is sensitive to short-wavelength light energy. These receptors send information about light and darkness to the suprachiasmatic nuclei (SCN) in the hypothalamus of our brain, which is the center of the body's internal clock [20]. In the presence of bright light, the SCN sends signals to the appropriate brain nuclei to modulate the release of serotonin and cortisol, leading to alertness and making us feel energetic. On the other hand, in the absence of enough light, the SCN signals the pineal gland to secrete melatonin, which makes us feel drowsy or sleepy [21]. Regular exposure to light and dark cycles causes a stable sleep–wake cycle and better sleep quality. In the absence of proper 24 h light and dark stimulus, the circadian rhythm is disrupted, leading to disturbed sleep, sleepiness during the day, fatigue, depression, and numerous other related health issues. Therefore, the entrainment of the circadian rhythm with the appropriate light stimulus is essential for the proper working of our body and consequently our health and sleep.

The circadian rhythm and sleep regulation have an important influence on the cognitive processes of the human body, including mood, learning, memory, alertness, and reaction time. In tune with the 24 h circadian cycle, cognitive function shows a similar 24 h cycle, starting low in the morning, becoming high after a few hours, and remaining high until bedtime [18]. Sleep plays a key role in cognitive performance, and its disruption can cause a reduction in several cognitive processes such as arousal, attention, and working memory. Cognitive performance is regulated by a back-and-forth interaction between the sleep–wake cycle and the circadian rhythm, and its misalignment can cause a significant decrease in performance [22]. Therefore, regulating the circadian cycle helps to regulate cognitive function among building occupants.

Another circadian impact of lighting is on the mood of people. In psychology, mood is defined as "a group of persisting feelings associated with evaluative and cognitive states which influence all the future evaluations, feelings and actions" [23]. In the presence of high intensities of blue-enriched light, our body releases serotonin, also known as the "happy hormone", which leads to the improvement of the mood of people who spend significant time indoors [22]. The seasonal variation of natural light can result in depressive symptoms due to lower duration and intensities of light exposure during shorter days in winter months [24], showing the importance of daylight exposure for mental health. This suggests that daylighting design, which acts as the primary source of sunlight exposure for many people, can have an important role in regulating the mood of building occupants.

Daylight is characterized by a wide spectrum of wavelengths and high levels of illuminance. These characteristics mean that daylight has a markedly different chronobiological effect on the circadian clock when compared to electric lighting [25]. Although short-wavelength electric lighting has also been known to stimulate melanopsin for regulating the circadian rhythm [26], studies show that daylighting provides stronger environmental time cues for regulating the human circadian clock as compared to electric lighting. Moreover, the typical electric lighting conditions in indoor spaces lack the requisite amount of intensity or spectral composition to regulate the circadian clock adequately, unlike daylighting. Consequently, daylighting leads to earlier bedtimes and improved sleep quality [19,27].

Earlier bedtimes due to daylighting are closely related to the timing of light exposure. The human circadian clock is the most sensitive to light stimuli during the biological night (approximately between 6 p.m. and 6 a.m.) and least sensitive during the middle of the day [19]. A consequence of electric lighting is exposure to light during the evening which leads to circadian phase delays and later bedtimes. On the other hand, daylighting leads to light exposure in the early mornings and minimizes light exposure during late evenings, leading to circadian phase advancement and earlier bedtimes [25]. An implied benefit associated with daylighting among office workers is that they will be able to maintain earlier sleep–wake timing for their work schedules, and the disruption of their circadian cycle resulting in various cognitive and health consequences will be reduced [27].

3. Daylighting Properties That Impact Circadian Rhythm

Lighting is characterized by the intensity, spectrum, duration of exposure, and timing of the exposure. Therefore, any study on daylighting is incomplete without understanding how these aspects of lighting impact the circadian rhythm of participants. There are a few studies that have explored how each characteristic of lighting has an impact on the entrainment of the circadian rhythm.

Light intensity: One of the basic attributes of lighting is its intensity or brightness. The intensity of light can be measured in several ways, the most common being its illuminance, defined as the amount of luminous flux per unit area and measured in lux. Several studies show that the intensity of light has a significant impact on the circadian rhythm and human health. This is supported by the fact that light intensity affects the magnitude of melatonin suppression, which is an established circadian phase marker [21]. In a study measuring the impact of light intensity on the circadian system [19], participants were exposed to 6.5 h of light stimulus with illuminance varying from 3 to 9000 lux. They were observed to have minimal circadian system responses below 100 lux, while saturation occurred around 1000 lux. The responses were more pronounced after spending prolonged periods in darkness. However, these were preliminary findings and research on the quantification of intensity sensitivity is ongoing.

From a design perspective, in order to provide high illuminance levels in building interiors, it is necessary to rely on daylighting as a supplemental source of light, as electric lights alone cannot provide high light levels due to energy code requirements.

Light spectrum: The spectrum or wavelength of light plays a major role in the regulation of circadian rhythm, as short-wavelength light has an increased effect on the suppression of melatonin which leads to a reduction in sleepiness and better cognition due to increased alertness [18]. According to a study examining the impact of the light spectrum on the circadian cycle [19], a 6.5 h exposure to light of 460 nm and 555 nm showed that shorter wavelength exposure caused greater melatonin suppression, and the participants were significantly more alert with faster reaction times. As daylight is rich in the entire light spectrum, the spectral impacts of lighting are mostly studied under electric lighting whose composition can be easily manipulated. Studies conducted under controlled laboratory settings [28,29] have quantified the spectral sensitivity of various intensities of light for circadian entrainment by melatonin suppression, and these findings have been used to derive circadian metrics such as the Circadian Stimulus [30] and Equivalent Melanopic Lux [31] for the circadian impacts of lighting. However, these metrics do not fully account for the temporal aspects of light exposure such as the duration and timing of exposure.

Timing of light exposure: Studies show that the timing of light exposure has an impact on the direction and magnitude of the circadian response to the light stimulus. Early morning light exposure leads to an increase in alertness during the day, while light exposure in the middle of the day causes alertness later at night [21]. The advent of electric light has led to light exposure during nighttime, which increases the risk of developing circadian rhythm sleep–wake disorders [25]. In a study measuring the lighting impacts on human circadian rhythm [19], subjects were most sensitive to nighttime light exposure and least sensitive to light stimuli in the middle of the day. The "un-timely" light stimuli were able to cause large shifts in the circadian phase by over 12 h. While the exact boundaries of the timing of light exposure have not yet been defined, Andersen et al. [32] have defined three distinct timings for circadian entrainment. Morning light exposure (06:00–10:00 h) causes most people to experience an advancement of the circadian phase, mid-morning light exposure (10:00–18:00 h) causes subjective alertness without shifting the circadian cycle, while nighttime light exposure (18:00–06:00 h) can cause disruption of the circadian cycle, and therefore circadian effective light should be avoided during this time.

Duration of light exposure: Research has shown that a longer duration of exposure to light pulses is responsible for greater amounts of shifts in the circadian phase [21]. In a study testing the effects of the duration of light exposure on the circadian cycle [19], researchers found that intermittent bright light exposure produced similar results as compared to continuous light exposure, so long as the overall duration is similar, and the magnitude of response to duration is not linearly related but rather the effect flattens with time. This implies that the variability of daylight availability is not a major cause for concern because the duration of circadian lighting can be interrupted without any significant difference in its effectiveness. Moreover, an extremely high level of daylight does not produce any meaningful benefit, and therefore controlling daylight for glare should not adversely affect the circadian daylighting potential of an indoor space.

4. Relationship Between Duration and Intensity of Circadian Effective Light

As mentioned earlier, the effect of the duration and intensity of daylight exposure on the circadian rhythm are inversely proportional to each other. In other words, shorter durations of higher intensities of light can produce similar effects on the circadian cycle as longer durations of lower intensities of light exposure. These manifest in the form of effects on our mood and sleep patterns. In a study by Dewan et al. [33], 56 healthy young adults were exposed to light levels of 2000 lux, 4000 lux, and 8000 lux, for 1, 2, and 3 h durations for each intensity, and their melatonin levels were measured using blood samples. They found that the 3 h duration of exposure was better than 1 h of exposure in suppressing melatonin but there were no significant differences in the effects of the three illuminance levels, showing that moderate intensity light exposures of longer durations are more effective than shorter durations of higher intensities of light. However, it is important to note that even the lower intensities used in this study are considered to be a high intensity of light in everyday conditions, and intensities higher than 2000 lux often produce glare.

Several studies on the use of bright light therapy to treat Seasonal Affective Disorder (or SAD) have explored the quantities of the duration and intensity of light exposure in reducing the levels of depression in participants [34–36]. Desan et al. [34] found that white light exposure (at peaks of 464 nm and 564 nm) of 1350 lux for 30 min before 8 a.m. was significant in reducing depression among 23 adults suffering from SAD. Similarly, Meesters et al. [35] found that exposure to 750 lux of blue-enriched light (17,000 K) and 10,000 lux of white light (5000 K) for 30 min was equally effective in the treatment of SAD. However, the authors note that the light receptors may have been subjected to the saturation effects of the high illuminance levels in order to produce similar effects in both light treatment conditions. Gradisar et al. [36] used bright light therapy along with cognition behavior therapy to treat delayed sleep phase disorder among 49 adolescents in a randomized controlled trial and found that exposure to illuminances of 1000 lux of white light or sunlight, when available, for 30 min was significant in improving various sleep impairments among participants.

Multiple sleep studies have also reported quantitative data about the duration and intensities of light exposure in improving sleep [37–39]. Leppämäki et al. [37], found that simulated dawn in South Finland with inadequate daylight during winter was able to improve subjective sleep quality among 77 adults who acted as their control. The dawn simulators used in this study were electric light sources that emitted gradual light up to 200–300 lux for 30 min and the treatment results were visible for 6 days but did not persist once the treatment stopped. In another study, Sharkey et al. [38], found that 225 lux of blue light (470 nm) for 1 h within 15 min of waking up, did not advance the circadian phase of the participants measured by salivary melatonin levels. However, advancing their sleep schedules to correspond with the natural light/dark cycle was effective in obtaining significant circadian phase shifts among the participants. In a study by Yoon et al. [39], 14 patients were subjected to light therapy of 360 lux (6000 K, peak wavelength 480 nm) for 25 min before 9:00 a.m. for 2 weeks. The participants showed an improvement in subjective daytime sleepiness and sleep quality, but salivary cortisol levels did not show any significant changes, likely due to a very small sample size.

These studies provide some quantitative information about the duration and intensity of light exposure which can bring about significant improvement in circadian health and, in turn, the sleep and mood of people. However, none of the metrics that measure daylight, even those that account for circadian light, have incorporated the relationship between the duration and intensity of light exposure.

5. Existing Daylighting Design Metrics

One of the biggest challenges facing daylighting design is the lack of availability of an appropriate, universally accepted daylighting metric. This is primarily because different stakeholders prioritize different aspects of daylighting, ranging from energy savings to architectural visual performance to cost efficiency. Additionally, performance metrics for daylighting can be very difficult to create due to the multifaceted nature of daylighting and its dynamic availability [40]. Historically, daylighting metrics were static, which accounted for a fixed point in time, the most prevalent being the daylight factor.

Daylight factor: The daylight factor (DF) has historically been the most commonly used static metric and was a part of numerous energy rating systems and codes until very recently [40]. It is defined as the ratio of indoor daylight illuminance at a point on a horizontal plane to simultaneous external illuminance on an unobstructed plane under overcast sky conditions [41]. This metric was very easy to use and, therefore, had gained widespread popularity; however, it only accounts for overcast sky conditions as the "worst case scenario" and does not measure lighting in partially cloudy or clear sky conditions, making it a poor metric for the generalization of daylighting under other sky conditions. The overly simplified static model therefore did not work for effective daylighting, and complex hourly simulation methods had to be developed [42].

The changing nature of daylight availability throughout the day as well as across seasons generates the need for dynamic daylighting metrics which account for daylight availability across a period by using a time series of illuminance values to evaluate daylighting [40]. The computation of dynamic daylighting is very complex to do by hand; therefore, it is calculated mostly using computer simulations. That is why dynamic metrics have gained popularity only in recent times with the availability of computing systems. These metrics are climate, location, and orientation-dependent, which guide the design of shading devices while accounting for glare [42].

There are several dynamic daylighting metrics whose basic approach can be generalized under Climate-Based Daylight Modeling (CBDM), where annual daylight levels are predicted using simulations that use sky models derived from hourly weather data of a particular location [42]. The metrics that use the CBDM differ in the criteria that they use to determine "adequate" daylighting at a particular time and place, some of which are mentioned below:

Daylight Autonomy (DA): DA gives a measure of the percentage of time during which the daylight illuminance levels meet or exceed a previously set threshold usually based on task requirements. It uses work plane illuminance (the light level at the horizontal work surface) as the evaluation criteria to determine if there are sufficient light levels for a particular task under daylighting alone [40].

Useful Daylight Illuminance (UDI): UDI is similar to DA but improves upon it by adding an upper limit that excludes glare conditions to account for visual comfort [43]. UDI also uses work plane illuminances to set a minimum threshold for meeting task lighting requirements using daylight alone. It essentially evaluates the percentage of occupied times in a year when the lighting falls within the range of neither too dark (usually less than 100 lux) nor too bright (more than 2000 lux) [40].

Continuous Daylight Autonomy (cDA): cDA is another approach similar to DA which provides partial credit for task lighting using daylight alone which falls below the lighting threshold for the task. The partial credit is calculated as the ratio of the daylight level to the required threshold. In this metric, even partial lighting provided by daylighting is considered beneficial [40]. However, in this metric, there is no upper threshold like UDI to account for glare.

Spatial Daylight Autonomy (sDA): sDA adds a spatial element to the quantification of DA. It is "an annual daylighting metric that quantifies the fraction of the area within a space for which Daylight Autonomy exceeds a specified value" [42]. Just like cDA, this metric also does not account for any upper limit for glare prevention. This is the most commonly accepted IES-approved method for defining daylighting performance in simulation models.

Annual Sunlight Exposure (ASE): To account for the glare potential of daylighting, IES has recommended the use of ASE, which gives the percentage of interior space that receives at least 1000 lux for at least 250 annual occupied hours [42]. This metric is used in conjunction with sDA to evaluate both task lighting as well as the glare potential of the analysis area.

While these metrics are a good starting point for measuring daylighting, they focus only on illuminance levels and generally account for visual tasks and the energy-saving potential of daylighting. They are also oriented towards task lighting, which is typically lighting on the horizontal work surface. Lighting for the regulation of the circadian rhythm needs to be measured on the vertical surface in front of the viewer's eyes and can often have very different illuminance values than the horizontal task plane lighting within the same space. Moreover, these daylighting metrics are based on the illuminance levels of daylight and do not account for other variables of daylighting such as the spectrum, duration (per day), and timing. Therefore, there is a need for daylighting metrics focusing on the non-visual impacts of light, such as the entrainment of the circadian cycle using all the relevant variables of daylighting.

6. Existing Circadian Lighting Metrics

There is some emerging research on lighting metrics based on the entrainment of the circadian cycle. These metrics are based on the minimum illuminance levels of different spectra of incident light which are required for entraining the circadian rhythm. They are calculated using mathematical relationships that have been derived based on the findings of some highly controlled lab-based studies [28,29] that evaluated the relationship between illuminance and spectrum for melatonin suppression. In these studies, the subjects were exposed to different intensities and spectra of light directed directly into their eyes in the middle of the night after a period (2–3 h) of complete darkness, and their melatonin levels were monitored. The results of these studies have created an action spectrum graph that gives information about the intensities at which different wavelengths of light are most effective in suppressing melatonin. They have also identified the wavelengths of light that are most sensitive for melatonin suppression, and therefore most effective in the regulation of the circadian rhythm. Moreover, these metrics evaluate both electric light and daylight and require information about the spectral power distribution of the incident light, which is often not very easily available.

Circadian Stimulus (CS): The Circadian Stimulus is a circadian-based lighting metric that evaluates the circadian potential of interior lighting based on both the intensity and spectrum of incident light [30]. This metric computes the value of circadian light called CL_A based on the melatonin action spectrum graphs from studies by Brainard et al. [28] and Thapan et al. [29] which provide the effectiveness of various wavelengths of light on melatonin suppression, which in turn regulates circadian rhythm. This metric is based on the premise that the spectral sensitivity of the circadian system is governed by all known photopigments, not just melanopsin. The value of CL_A is converted to the Circadian Stimulus, which is proportional to the percent nocturnal melatonin suppression and is measured on a scale of 0–0.7. The CS metric measures the effectiveness of a light source (whether daylight or electric) with a known SPD in suppressing melatonin, with a value of 0 signifying no effect and 0.7 signifying the maximum melatonin suppression achievable after 1 h of exposure to the light source. The computation can be conducted using an online website created by the authors [30], which requires the intensity and spectral power distribution (SPD) of the incident light to compute the Circadian Stimulus. It also has several predefined special power distribution values of common electric lamps and daylighting conditions.

The validity studies conducted by the creators of this measure show that exposure to a CS value greater than 0.3 leads to improved sleep among building occupants, while a value less than 0.15 is considered too low for an adequate Circadian Stimulus [30]. However, this metric does not account for timing, duration, and prior light exposure which also have a substantial impact on the circadian response to lighting. Most importantly, it does not deal with the period of darkness required as a part of the circadian cycle. While the metric itself does not incorporate temporal aspects, studies using this metric show that exposure to CS of **0.3 or greater for at least 1 h in early mornings** is enough for the entrainment of the circadian rhythm [30].

Equivalent Melanopic Lux (EML): This is the accepted metric in the WELL building standard (used to certify building performance based on human health and well-being), which evaluates the melanotic spectral response for circadian entrainment by converting the data from light intensity and spectral power distribution (SPD) to their corresponding illuminance value based on the spectral sensitivity function of melanopsin [31]. In other words, EML only accounts for responses facilitated by the melanopsin pigment in the retina of the eye and not the rods and cones. Since melanopsin is believed to be the primary pigment for circadian entrainment, EML in short provides a measure of circadian effective light by multiplying the illuminance (in lux) of the light to a melanopic ratio that is calculated using the spectral characteristics of the light. The user inputs the light intensity (illuminance) and selects a predefined spectral power distribution, or they directly input the spectral power distribution which is converted to an EML value in lux by the Excel toolkit, which is freely available online. The WELL building standard has set some minimum thresholds for circadian entrainment for different environments with an EML value of 200 lux, a value that is the most general lighting level for most spaces [31]. This measure also lacks validated data regarding the timing and duration of exposure, which has a very important effect on circadian entrainment.

However, the WELL building standard does specify the plane of measurement as vertical facing forward and 1.2 m above the finished floor and the timings of durations of exposure to meet its circadian lighting design requirements as mentioned below (Table 1).

Table 1. WELL building standard circadian lighting design minimum thresholds [44].

	Work Areas		Living Env. (Daytime)	Living Env. (Nighttime)	Breakrooms	Learning Areas
Spatial requirement	75% or more workstations	All workstations	Center of room facing wall	0.76 m above finished floor	Average across entire room	75% or more desks
EML levels	200 EML or more	150 EML or more	200 EML or more	50 EML or less	250 EML or more	125 EML or more
Timing/duration	9 a.m.–1 p.m. every day					At least 4 h every day

Melanopic Equivalent Daylight Illuminance (mEDI): The CIE (Commission Internationale de l'éclairage or the International Commission on Illumination) has adopted an updated version of EML called mEDI [45], which weighs the effective rate of photon capture by the melanopsin pigment under a given light condition to the illuminance that a standard (D65) daylight spectrum would produce the same rate of photon capture. Essentially, mEDI converts the photopic measurement of light to account for the spectral sensitivity of the melanopsin so that the lux values can be standardized to obtain a threshold for light levels that entrain the circadian rhythm. Just like EML, this measure also gives the melanopic response to light [46].

Just like CS and EML, mEDI by itself does not define lighting requirements for circadian entrainment, nor does it incorporate any temporal aspects within its values, but a team of experts [47] have defined threshold values with timing/duration parameters for this metric. During the daytime, they recommended a minimum mEDI of 250 lux at the eye measured on a vertical plane at 1.2 m height which should be met with daylight if available or electric light enriched in shorter wavelengths. On the other hand, in the evenings (3 h before bedtime), the maximum mEDI should be 10 lux, and at nighttime, the maximum mEDI should be 1 lux at eye level [47].

While CS and EML/mEDI are the most commonly used circadian lighting metrics, due to the highly evolving research about the role of various photoreceptors on circadian entrainment, there are many new emerging metrics to measure the circadian effects of light. Research also shows that apart from the direct light measures, the reflected component based on the color of the interior finishes impacts the circadian rhythm of occupants [48]. Several other researchers have used the spectral power distribution of light to evaluate daylighting which accounts for the circadian response of indoor occupants [43,49,50] but have not considered timing and duration as factors. There have also been some attempts to create simulation-based circadian daylighting metrics.

7. Developing Metrics and Circadian Daylight Simulation Workflows

A number of daylighting metrics are being developed that are based on simulation workflows that can aid designers at various design stages:

Lightsolve: Lightsolve was created as an approach for daylight design during the early design stages, which laid out an iterative workflow to model various daylighting parameters such as illuminance, visual comfort, and thermal parameters among others, and to meet a set of lighting goals [43]. It was improved upon by including a simulation framework that included the non-image forming effects of daylight, which uses Radiance to simulate daylight and displays annual daylight "performance" in terms of its circadian potential, termed as the non-visual effects of light [51].

Non-Visual Direct-Response (nvR_D) Model: The non-visual direct response or nvR_D model was developed by Amundadottir [52] to create a light-driven prediction model for alertness. It simulates the light incident at eye level using Radiance daylight simulation and evaluates the cumulative non-visual health potential of the incident light over 24 h. The nvR_D model is derived from nocturnal melatonin suppression response studies that account for the intensity, wavelength, prior exposure, and duration of exposure to light. It accounts for the non-linear sensitivity of the ipRGCs of our eyes due to prolonged light exposure, and its value is computed by simulating a series of luminance/illuminance values at 6 min intervals which are integrated over time to give a cumulative response RD. This cumulative response is a measure of the daily light dose and can be modified for other durations of time (shorter than 24 h) to provide a cumulative light dose for that period. In a case example by the authors of this metric, the cumulative response RD was measured on a scale of 0–9, and a value of 4.2 was set as the threshold for non-visual health potential. A study using 1000 Lux polychromatic light exposure over 5 h was used as the reference to reach this threshold [52].

The nvR_D model is effective for predicting the alerting effect of prolonged exposure to different daylighting conditions but it was not designed to predict circadian effectiveness. While the nvR_D model accounts for the duration of light exposure and how our eyes adjust to prolonged exposure to different intensities of light, it does not factor in the timing of exposure. This limits the potential of this measurement to act as an effective circadian lighting metric as the timing of light exposure is a very important factor in how the human circadian rhythm responds to different light stimuli. Moreover, when calculating the cumulative response, it starts the prior history from 0 and assumes that the person will have no light exposure before the start of the simulation. It also does not work for point-in-time evaluations as it depends on a series of past inputs to work.

Lark Spectral Lighting: This is a Grasshopper workflow used to evaluate circadian lighting using Radiance for daylight simulations. Radiance uses a 3-channel RGB spectrum of light. However, to accurately simulate the higher resolution of the spectral power distribution of light to calculate circadian lighting using the existing circadian metrics such as CS and EML, the Lark spectral lighting tool has been developed, which increases the resolution of Radiance spectral simulations to nine channels [53]. The inputs include the building geometry on Rhino 3D (v7) along with interior materials, the location of analysis either as an individual point or a sensor grid, the details of the daylight analysis period, the weather data file of the location, the time interval of analysis, and the spectral power density (SPD) of the sky (either as the default D65 or as user input). The outputs include spectral irradiances to compute mEDI and a graphical visual output of the illuminances. This workflow also features the nvR_D model by simulating annual daylighting at 6 min intervals to find the alerting potential of an architectural space [54].

This tool is very useful for the conversion of weather data to nine-channel spectral irradiances, which can be used to compute circadian lighting. Lark uses the CIE sky models along with measured data to model the daylight spectra whose variability in color is accounted for using associated CCT values for different sky types (overcast, intermediate, or clear) obtained from the weather data. The CCT is then converted to daylight spectral data based on CIE standard illuminants. However, it assumes a uniform color throughout the sky dome and does not account for changes in the spectral content over the sky dome [53].

Adaptive Lighting for Alertness (ALFA): This is a Rhino 3D plugin that is independent of the Grasshopper platform and is an alternative to using Lark (v2.0) for computing spectral irradiances for circadian lighting. It also uses Radiance for lighting simulations but increased its resolution from 3 channels to 81 channels [55]. It provides the EML value for an array of view positions within the lighting environment being analyzed and can compute lighting for electric sources as well. Its inputs include the Rhino 3D model, location, time, and the reflectance of surface materials [56].

ALFA (v1) uses a spectral sky generated from a pre-computed spectral sun and sky using measured atmospheric profiles in a radiative transfer library called libRadtran. Therefore, users can only input sky conditions but cannot use measured data. The variability of the sky is modeled in the SPD of the sky dome generated in ALFA [56]. However, ALFA is only capable of static single point-in-time simulation. This was extended to create dynamic annual simulations using the Lightsolve method using 56 simulation timesteps [57].

Occupant Well-being through Lighting (OWL): The Lark spectral model was improved upon by Maskarenj et al. (2022) to develop the OWL framework, which also uses a Grasshopper-based algorithm for lighting calculations. It uses the Perez Sky Model to conduct Radiance-based simulations in order to evaluate the luminance from the observer's viewpoint and convert this to CCT to calculate patch spectral power densities [46]. Although OWL uses the Perez Sky Model, it allows users to choose to run simulations based on CIE standard skies. The sky is divided into multiple patches and the luminance is generated using Radiance, which is then converted into corresponding CCT values. The CCTs are used to calculate the SPDs of the various sky patches using the CIE 015 standard document, which are then treated as separate light sources and merged to generate combined SPD data for the entire sky dome [46].

In other words, it uses weather data to estimate the SPD of the sky dome and generates a more accurate daylight simulation to calculate CS and EML values in interior spaces. This tool also takes the weather data and the Rhino 3D model as inputs, generates the SPD data, and evaluates circadian lighting in terms of CS, EML, and mEDI. The results for circadian lighting are displayed in a graphical format for selected days in a year in hourly increments of time. This tool is, however, limited as it simply displays the values of existing circadian metrics such as CS and EML, but does not evaluate the circadian sufficiency or account for timing or durations of exposure.

Circadian Design Assist Tool (CDAT): The Circadian Design Assist Tool was developed by Konis [58] to overcome the limitations of previous point-in-time workflows and to create an annual hourly simulation of EML to explore whole-building solutions. It uses Lark components to simulate the lighting spectrum for both daylight and well as electric light, and then integrates this with its own metric called Circadian Frequency which uses a CBDM approach to evaluate the annual performance of an entire space.

Circadian Frequency (CF) measures the percentage of days in a year during which a view vector (defined by an arrow at a position and pointing towards a potential view direction that receives incident light) meets or exceeds a given EML threshold throughout each daily analysis period. Its case example used the WELL building standard to define 200 EML as the threshold between the times of 7:00 and 13:00 [58]. The CF can be mapped on a grid with numerous points in an architectural model for multiple possible positions and view directions. A color gradient is used to show the circadian adequacy of various view vectors in a spatial grid, which are labeled as “Circadian Effective” if the CF value exceeds 75% and “Biologically Dark” if the CF value is less than 25%, with the values in between representing intermediate regions between the two. This metric leaves the determination of the timing and threshold value of EML up to the user to define.

CDAT is useful for evaluating the circadian potential of a space based on a fixed threshold of light exposure during a specified period of time in the day. However, the entrainment of the circadian rhythm requires different thresholds for different times of the day (morning lighting thresholds will vary from evening thresholds). While the CF metric can account for a specific block of time, it cannot work with multiple timing blocks (such as afternoon or evening) which may require different threshold values. Moreover, the CF metric does not factor in the relationship between the intensity and duration of light exposure, which would need a dynamic threshold value such that longer durations of light exposure would need lower intensities of EML/mEDI or vice versa.

8. Critique of Existing Metrics and Discussion

Light exposure plays an essential role in the synchronization of the human circadian clock which in turn impacts our sleep, cognitive performance, and mood, among other things. Even though electrical lighting can provide the required light stimulus for circadian entrainment, studies have shown that daylight stimulus is often more effective for the entrainment of the circadian cycle. Furthermore, studies have also shown that the human circadian rhythm is impacted by the various aspects of daylight exposure.

Light intensity: Higher intensities of light exposure during the day suppress melatonin, which causes more alertness during the day and better sleep at night. Exposure to higher intensities of light has also been shown to improve cognitive performance as well as people's moods, but it reaches saturation at intensities greater than 1000 lux.

Light spectrum: Short-wavelength light or "blue light" is more effective in melatonin suppression due to the presence of short-wavelength sensitive receptors in our eyes which are responsible for the entrainment of the circadian rhythm. Since sunlight is rich in short-wavelength light, including in the mornings, it helps to improve cognitive performance, sleep, and mood.

Timing of exposure: Exposure to short-wavelength, high-intensity light in the morning is more effective in entraining circadian rhythm. Afternoon exposure to such light is not as effective, and evening exposure to such light can disrupt the circadian cycle. Long-wavelength, low-intensity light is recommended in the evenings for better sleep and mood.

Duration of exposure: Longer durations of light exposure are more effective in entraining the circadian cycle. However, sometimes shorter durations of higher intensities of light exposure can be as effective as longer durations of low intensities of light exposure, so their relationship needs to be quantified and explored.

View direction: Apart from these, the direction and position of the light measurement are important as we often measure light on the horizontal work plane meant for task lighting, but circadian lighting should be incident on the user's eyes. Therefore, measuring light on the vertical plane at eye level is a better predictor of circadian effectiveness as compared to a typical horizontal work plane measurement.

Daylight naturally provides a lot of the requirements for circadian entrainment but there is a shortage of proper daylighting metrics for circadian lighting that can help designers during the building design phase. Originally, daylight metrics were static, such as the daylight factor which is inadequate for the proper evaluation of daylight due to its dynamic nature of availability. This was resolved by the advent of computer simulations, which led to the rise of various dynamic daylighting metrics such as Daylight Autonomy, Useful Daylight Illuminance, and Continuous Daylight Anatomy. While these measures are good for computing annual illuminance levels, they do not account for circadian lighting by themselves.

From this review of existing studies and existing metrics, one can see that certain daylighting metrics such as Circadian Stimulus and Equivalent Melanopic Lux give a measure of circadian lighting by using data from controlled clinical studies. Researchers and the adopters of these metrics have defined threshold values, and meeting these would allow most people to obtain adequate lighting for circadian entrainment.

The metrics for circadian lighting only account for a fixed point in time, so several researchers have come up with simulation-based tools that can help to calculate circadian lighting over a range of time. Lark is a spectral simulation tool that uses weather data and building geometry to generate spectral radiances of the sky using Radiance in Grasshopper and then converting them to CS and EML. However, it uses a fixed SPD that is uniform across the sky dome, which is solved by the OWL workflow on Grasshopper that uses the weather file to create sky patches for different time periods and creates the SPD of each skydome for better simulation results. It also calculates the SPD for different patches of the sky dome and then combines them for a relative SPD for the entire sky. On the other hand, ALFA generates the spectrum using the libRadtran library using a fixed atmospheric profile but accounts for variability in the SPD of the sky dome. An advantage of Lark and OWL is that they are modeled on Grasshopper and their components are available to build upon by other users and tool developers. However, ALFA is not a part of the Grasshopper ecosystem, so it cannot be built upon, unlike Lark and OWL. Although ALFA is three times faster than Lark, Lark outperforms ALFA in terms of accuracy [59]. A comparison between the various circadian lighting simulation tools has been included (Table 2).

Table 2. Comparison between various circadian lighting simulation tools.

	Lark	**ALFA**	**OWL**	**CDAT**
Light source	Daylight/Electric Light	Daylight/Electric Light	Daylight/Electric Light	Daylight/Electric Light
Metric	mEDI, nvR_D	EML	CS, EML, mEDI	CF, EML
Rendering engine	Radiance	Radiance	Radiance	Radiance
Software	Rhinoceros Grasshopper	Rhinoceros	Rhinoceros Grasshopper	Rhinoceros Grasshopper
Other components	-	-	Lark	Lark
SPD skydome	Uniform	Non-Uniform	Non-Uniform	Uniform
Sky source	CIE	libRadtran	Perez, CIE	CIE

Another issue is that all three tools simply output the values of CS and EML/mEDI for different points of time without evaluating whether these are adequate lighting or not. This issue has been partially addressed by the CDAT, which uses Lark to generate spectral irradiances but displays circadian lighting adequacy in terms of a graphic of "circadian effective" and biologically dark zones in the building geometry. This tool accounts for morning daylight exposure but does not account for the duration of light exposure and its relationship to adequate intensity levels. Moreover, none of these tools address visual comfort issues such as glare or combination with electric light sources.

The circadian rhythm impacts of daylighting on the health of building occupants make it an essential component of healthy building design. While electric lighting can be designed to mimic daylighting, (and there have been studies with promising results [9,60]), commonly used office lighting often does not meet the levels required for circadian entrainment. Moreover, other benefits of daylighting are lost with electric substitutes. Daylighting often brings with it an aspect of "naturalness", including exterior views in the case of side windows, that has a positive effect on mental health and perceived satisfaction among people as compared to electric lighting [17,24,61,62].

The existing metrics for daylighting design, however, are woefully inadequate for use by lighting designers, especially from a perspective of circadian lighting. Table 3 highlights the various lighting properties that are addressed by the various circadian metrics and simulation tools. The three existing circadian lighting metrics, Circadian Stimulus (CS) [63], Equivalent Melanopic Lux (EML) [31], and Melanopic Equivalent Daylight Illuminance (mEDI) [45] only account for the intensity and spectrum of lighting at a fixed point in time. These metrics neither factor in the dynamic nature of daylighting, nor the temporal aspects of circadian lighting. In addition, the dynamic nature of daylighting itself makes it difficult to create mathematical relationships with the temporal aspects of lighting (the duration and timing of exposure), along with luminous aspects (intensity and spectrum).

Table 3. Lighting properties addressed by circadian metrics and simulation tools.

Lighting Properties	CS	EML	mEDI	Lark	nvR_D	ALFA	OWL	CDAT
Intensity	✓	✓	✓	✓	✓	✓	✓	✓
Spectrum	✓	✓	✓	✓	✓	✓	✓	✓
Duration					✓			
Timing								✓
View Direction				✓	✓	✓	✓	✓

✓—Properties addressed by the circadian metrics and simulation tools.

Daylighting metrics that do incorporate daylight's dynamic nature are usually simulation-based as they need to simulate the lighting for multiple points of time simultaneously. Many of these metrics, such as Daylight Autonomy (DA) [64] Spatial Daylight Autonomy (sDA) [65], and Useful Daylight Illuminance) (UDI) [66], were mainly developed for quantifying daylighting performance on the horizontal plane for task lighting and do not provide information to directly address light exposure for circadian entrainment. Recently, there have been some attempts to model dynamic daylighting metrics in combination with circadian metrics (such as CS and EML/mEDI) using daylight simulation tools [46,53,67,68]. However, they do not robustly incorporate the temporal aspect of circadian light into the metrics, and they also lack adequate validation due to a lack of testing in the real world.

The biggest challenge faced by researchers today is that the threshold values for proper circadian entrainment of measures such as the mEDI are dependent on temporal factors, namely the timing and duration of light exposure. However, there are not enough studies, especially in a controlled clinical setting, to provide enough direct data about these threshold values. The data from numerous clinical trials that measure the temporal factors individually can be interpolated to form mathematical relationships with luminous factors. Some studies have already attempted this separately for duration or timing but none of them have accounted for both the temporal factors simultaneously.

Although several studies show the various approaches to account for circadian effective daylighting, there is limited evidence of their validity in predicting the entrainment of circadian rhythm. Therefore, a need exists to combine dynamic daylighting metrics with circadian metrics and to incorporate temporal aspects such as the timing and duration of light exposure to create a more robust daylighting metric for circadian daylighting design. However, additional research is required to quantify temporal aspects for the evaluation of circadian-effective spaces which can provide guidance for the creation of a better circadian daylighting metric.

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References

1. Evans, G.W. The built environment and mental health. *J. Urban Health* **2003**, *80*, 536–555. [CrossRef] [PubMed]

2. Ander, G.D. Daylighting. In *Whole Building Design Guide*; National Institute of Building Sciences: Washington, DC, USA, 2016.
3. Guyon, D. Daylight dividends case study: Smith Middle School, Chapel Hill, N.C. *J. Green Build.* **2006**, *1*, 33–38. [CrossRef]
4. Ackley, A.; Donn, M.; Thomas, G. Measuring the lighting performance in a national school property portfolio. *Arch. Sci. Rev.* **2020**, *63*, 402–416. [CrossRef]
5. Widiastuti, K.; Susilo, M.J.; Nurfinaputri, H.S. How classroom design impacts for student learning comfort: Architect perspective on designing classrooms. *Int. J. Eval. Res. Educ.* **2020**, *9*, 469–477. [CrossRef]
6. Aarts, M.P.J.; Stapel, J.C.; Schoutens, T.A.M.C.; van Hoof, J. Exploring the impact of natural light exposure on sleep of healthy older adults: A field study. *J. Daylight.* **2018**, *5*, 14–20. [CrossRef]
7. Boubekri, M.; Cheung, I.N.; Reid, K.J.; Wang, C.-H.; Zee, P.C. Impact of Windows and Daylight Exposure on Overall Health and Sleep Quality of Office Workers: A Case-Control Pilot Study. *J. Clin. Sleep Med.* **2014**, *10*, 603–611. [CrossRef] [PubMed]
8. Münch, M.; Linhart, F.; Borisuit, A.; Jaeggi, S.M.; Scartezzini, J.L. Effects of prior light exposure on early evening performance, subjective sleepiness, and hormonal secretion. *Behav. Neurosci.* **2012**, *126*, 196–203. [CrossRef] [PubMed]
9. Shishegar, N.; Boubekri, M.; Stine-Morrow, E.A.L.; Rogers, W.A. Tuning environmental lighting improves objective and subjective sleep quality in older adults. *Build. Environ.* **2021**, *204*, 108096. [CrossRef]
10. Álvarez, S.P. Natural light influence on intellectual performance. A case study on university students. *Sustainability* **2020**, *12*, 4167. [CrossRef]
11. Baloch, R.M.; Maesano, C.N.; Christoffersen, J.; Mandin, C.; Csobod, E.; de Oliveira Fernandes, E.; Annesi-Maesano, I. Daylight and school performance in European schoolchildren. *Int. J. Environ. Res. Public Health* **2020**, *18*, 258. [CrossRef] [PubMed]
12. Nioi, A.; Roe, J.; Gow, A.; McNair, D.; Aspinall, P. Seasonal differences in light exposure and the associations with health and well-being in older adults: An exploratory study. *Health Environ. Res. Des. J.* **2017**, *10*, 64–79. [CrossRef]
13. Öner, M.; Kazanasmaz, T.; Leccese, F.; Salvadori, G. Analysis of the relationship between daylight illuminance and cognitive, affective and physiological changes in visual display terminal workers. *Build. Serv. Eng. Res. Technol.* **2020**, *41*, 167–182. [CrossRef]
14. Figueiro, M.G.; Steverson, B.; Heerwagen, J.; Kampschroer, K.; Hunter, C.M.; Gonzales, K.; Plitnick, B.; Rea, M.S. The impact of daytime light exposures on sleep and mood in office workers. *Sleep Health* **2017**, *3*, 204–215. [CrossRef] [PubMed]
15. Grimaldi, S.; Partonen, T.; Saarni, S.I.; Aromaa, A.; Lönnqvist, J. Indoors illumination and seasonal changes in mood and behavior are associated with the health-related quality of life. *Health Qual. Life Outcomes* **2008**, *6*, 56. [CrossRef]
16. Swanson, V.; Sharpe, T.; Porteous, C.; Hunter, C.; Shearer, D. Indoor annual sunlight opportunity in domestic dwellings may predict well-being in urban residents in scotland. *Ecopsychology* **2016**, *8*, 121–130. [CrossRef]
17. An, M.; Colarelli, S.M.; O'Brien, K.; Boyajian, M.E. Why we need more nature at work: Effects of natural elements and sunlight on employee mental health and work attitudes. *PLoS ONE* **2016**, *11*, e0155614. [CrossRef]
18. Fisk, A.S.; Tam, S.K.E.; Brown, L.A.; Vyazovskiy, V.V.; Bannerman, D.M.; Peirson, S.N. Light and cognition: Roles for circadian rhythms, sleep, and arousal. *Front. Neurol.* **2018**, *9*, 56. [CrossRef] [PubMed]
19. Duffy, J.F.; Czeisler, C.A. Effect of light on human circadian physiology. *Sleep Med. Clin.* **2009**, *4*, 165–177. [CrossRef]
20. De Kort, Y.A.W.; Veitch, J.A. From blind spot into the spotlight. *J. Environ. Psychol.* **2014**, *39*, 1–4. [CrossRef]
21. Lack, L.C.; Wright, H.R. Chronobiology of sleep in humans. *Cell. Mol. Life Sci.* **2007**, *64*, 1205–1215. [CrossRef] [PubMed]
22. Blatter, K.; Cajochen, C. Circadian rhythms in cognitive performance: Methodological constraints, protocols, theoretical underpinnings. *Physiol. Behav.* **2007**, *90*, 196–208. [CrossRef] [PubMed]
23. Amado-Boccara, I.; Donnet, D.; Olié, J.P. The concept of mood in psychology. *Encephale* **1993**, *19*, 117–122. [PubMed]
24. Beute, F.; de Kort, Y.A.W. The natural context of wellbeing: Ecological momentary assessment of the influence of nature and daylight on affect and stress for individuals with depression levels varying from none to clinical. *Health Place* **2018**, *49*, 7–18. [CrossRef]
25. Blume, C.; Garbazza, C.; Spitschan, M. Effects of light on human circadian rhythms, sleep and mood. *Somnologie* **2019**, *23*, 147–156. [CrossRef]
26. Barkmann, C.; Wessolowski, N.; Schulte-Markwort, M. Applicability and efficacy of variable light in schools. *Physiol. Behav.* **2012**, *105*, 621–627. [CrossRef] [PubMed]
27. Wright, K.P.; McHill, A.W.; Birks, B.R.; Griffin, B.R.; Rusterholz, T.; Chinoy, E.D. Entrainment of the human circadian clock to the natural light-dark cycle. *Curr. Biol.* **2013**, *23*, 1554–1558. [CrossRef]
28. Brainard, G.C.; Hanifin, J.P.; Greeson, J.M.; Byrne, B.; Glickman, G.; Gerner, E.; Rollag, M.D. Action spectrum for melatonin regulation in humans: Evidence for a novel circadian photoreceptor. *J. Neurosci.* **2001**, *21*, 6405–6412. [CrossRef] [PubMed]
29. Thapan, K.; Arendt, J.; Skene, D.J. An action spectrum for melatonin suppression: Evidence for a novel non-rod, non-cone photoreceptor system in humans. *J. Physiol.* **2001**, *535*, 261–267. [CrossRef] [PubMed]
30. Rea, M.S.; Figueiro, M.G. Light as a circadian stimulus for architectural lighting. *Light. Res. Technol.* **2018**, *50*, 497–510. [CrossRef]
31. Lucas, R.J.; Peirson, S.N.; Berson, D.M.; Brown, T.M.; Cooper, H.M.; Czeisler, C.A.; Figueiro, M.G.; Gamlin, P.D.; Lockley, S.W.; O'hagan, J.B.; et al. Measuring and using light in the melanopsin age. *Trends Neurosci.* **2014**, *37*, 1–9. [CrossRef] [PubMed]

32. Andersen, M.; Mardaljevic, J.; Lockley, S.W. A framework for predicting the non-visual effects of daylight-Part I: Photobiology-based model. *Light. Res. Technol.* **2012**, *44*, 37–53. [CrossRef]
33. Dewan, K.; Benloucif, S.; Reid, K.; Wolfe, L.F.; Zee, P.C. Light-induced changes of the circadian clock of humans: Increasing duration is more effective than increasing light intensity. *Sleep* **2011**, *34*, 593–599. [CrossRef] [PubMed]
34. Desan, P.H.; Weinstein, A.J.; E Michalak, E.; Tam, E.M.; Meesters, Y.; Ruiter, M.J.; Horn, E.; Telner, J.; Iskandar, H.; Boivin, D.B.; et al. A controlled trial of the litebook light-emitting diode (LED) light therapy device for treatment of Seasonal Affective Disorder (SAD). *BMC Psychiatry* **2007**, *7*, 38. [CrossRef]
35. Meesters, Y.; Dekker, V.; Schlangen, L.J.M.; Bos, E.H.; Ruiter, M.J. Low-intensity blue-enriched white light (750 lux) and standard bright light (10 000 lux) are equally effective in treating SAD. A randomized controlled study. *BMC Psychiatry* **2011**, *11*, 17. [CrossRef]
36. Gradisar, M.; Dohnt, H.; Gardner, G.; Paine, S.; Starkey, K.; Menne, A.; Slater, A.; Wright, H.; Hudson, J.L.; Weaver, E.; et al. A randomized controlled trial of cognitive-behavior therapy plus bright light therapy for adolescent delayed sleep phase disorder. *Sleep* **2011**, *34*, 1671–1680. [CrossRef]
37. Leppämäki, S.; Meesters, Y.; Haukka, J.; Lönnqvist, J.; Partonen, T. Effect of simulated dawn on quality of sleep-a community-based trial. *BMC Psychiatry* **2003**, *3*, 14. [CrossRef]
38. Sharkey, K.M.; Carskadon, M.A.; Figueiro, M.G.; Zhu, Y.; Rea, M.S. Effects of an advanced sleep schedule and morning short wavelength light exposure on circadian phase in young adults with late sleep schedules. *Sleep Med.* **2011**, *12*, 685–692. [CrossRef]
39. Yoon, J.; Heo, S.; Lee, H.; Sul, E.; Han, T.; Kwon, Y.-J. Feasibility and Efficacy of Morning Light Therapy for Adults with Insomnia: A Pilot, Randomized, Open-Label, Two-Arm Study. *Medicina* **2023**, *59*, 1066. [CrossRef]
40. Reinhart, C.F.; Mardaljevic, J.; Rogers, Z. Dynamic daylight performance metrics for sustainable building design. *Leukos* **2006**, *3*, 1–25. [CrossRef]
41. Moon, P.; Spencer, D.E. Illumination from a non-uniform sky. *Illum. Energy* **1942**, *37*, 707–726.
42. Konis, K.; Selkowitz, S. *Green Energy and Technology Effective Daylighting with High-Performance Facades Emerging Design Practices*; Springer: Cham, Switzerland, 2017.
43. Andersen, M.; Kleindienst, S.; Yi, L.; Lee, J.; Bodart, M.; Cutler, B. An intuitive daylighting performance analysis and optimization approach. *Build. Res. Inf.* **2008**, *36*, 593–607. [CrossRef]
44. International WELL Building Institute. *The WELL Building Standard Version 1 (WELL v1)—Q4 2020*; Feature 54; International WELL Building Institute: New York, NY, USA, 2020.
45. Price, L. *CIE S 026 Alpha-Opic Toolbox*; International Commission on Illumination (CIE): Vienna, Austria, 2020. [CrossRef]
46. Maskarenj, M.; Deroisy, B.; Altomonte, S. A new tool and workflow for the simulation of the non-image forming effects of light. *Energy Build.* **2022**, *262*, 112012. [CrossRef]
47. Brown, T.M.; Brainard, G.C.; Cajochen, C.; Czeisler, C.A.; Hanifin, J.P.; Lockley, S.W.; Lucas, R.J.; Münch, M.; O'hagan, J.B.; Peirson, S.N.; et al. Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults. *PLoS Biol.* **2022**, *20*, e3001571. [CrossRef]
48. Kim, I.T.; Choi, A.S.; Sung, M.K. Development of a Colour Quality Assessment Tool for indoor luminous environments affecting the circadian rhythm of occupants. *Build. Environ.* **2017**, *126*, 252–265. [CrossRef]
49. Leslie, R.P.; Radetsky, L.C.; Smith, A.M. Conceptual design metrics for daylighting. *Light. Res. Technol.* **2012**, *44*, 277–290. [CrossRef]
50. Mardaljevic, J.; Heschong, L.; Lee, E. Daylight metrics and energy savings. *Light. Res. Technol.* **2009**, *41*, 261–283. [CrossRef]
51. Andersen, M.; Guillemin, A.; Amundadottir, M.L.; Rockcastle, S. Beyond illumination: An interactive simulation framework for non-visual and perceptual aspects of daylighting performance. In Proceedings of the BS2013—13th International Conference of the International Building Performance Simulation Association, Chambery, France, 25–28 August 2013.
52. Amundadottir, M.L.; Rockcastle, S.; Sarey Khanie, M.; Andersen, M. A human-centric approach to assess daylight in buildings for non-visual health potential, visual interest and gaze behavior. *Build. Environ.* **2017**, *113*, 5–21. [CrossRef]
53. Inanici, M.; Brennan, M.; Clark, E. Spectral daylighting simulations: Computing circadian light. In Proceedings of the 14th International Conference of IBPSA—Building Simulation 2015, Hyderabad, India, 7–9 December 2015; pp. 1245–1252. [CrossRef]
54. Gkaintatzi-Masouti, M.; van Duijnhoven, J.; Aarts, M.P.J. Simulations of non-image-forming effects of light in building design: A literature review. *Light. Res. Technol.* **2022**, *55*, 669–689. [CrossRef]
55. Balakrishnan, P.; Jakubiec, J.A. Spectral rendering with daylight: A comparison of two spectral daylight simulation platforms. In Proceedings of the Building Simulation Conference Proceedings, Rome, Italy, 2–4 September 2019; Volume 2, pp. 1191–1198.
56. Inanici, M.; Abboushi, B.; Safranek, S. Evaluation of sky spectra and sky models in daylighting simulations. *Light. Res. Technol.* **2023**, *55*, 502–529. [CrossRef]
57. Jakubiec, J.A.; Alight, A. Spectral and biological simulation methods for the design of healthy circadian lighting. In Proceedings of the 17th IBPSA Conference, Bruges, Belgium, 1–3 September 2021.

58. Konis, K. A circadian design assist tool to evaluate daylight access in buildings for human biological lighting needs. *Sol. Energy* **2019**, *191*, 449–458. [CrossRef]
59. Pierson, C.; Aarts, M.; Andersen, M. Validation of spectral simulation tools for the prediction of indoor daylight exposure. In Proceedings of the Building Simulation 2021: 17th Conference of IBPSA, Bruges, Belgium, 1–3 September 2021; Volume 17.
60. Zhu, Y.; Yang, M.; Yao, Y.; Xiong, X.; Li, X.; Zhou, G.; Ma, N. Effects of illuminance and correlated color temperature on daytime cognitive performance, subjective mood, and alertness in healthy adults. *Environ. Behav.* **2019**, *51*, 199–230. [CrossRef]
61. Gharaveis, A.; Yekita, H.; Shamloo, G. The perceptions of nurses about the behavioral needs for daylighting and view to the outside in inpatient facilities. *Health Environ. Res. Des. J.* **2020**, *13*, 191–205. [CrossRef]
62. Park, M.Y.; Chai, C.G.; Lee, H.K.; Moon, H.; Noh, J.S. The effects of natural daylight on length of hospital stay. *Environ. Health Insights* **2018**, *12*, 1178630218812817. [CrossRef]
63. Rea, M.S.; Figueiro, M.G.; Bierman, A.; Hamner, R. Modelling the spectral sensitivity of the human circadian system. *Light. Res. Technol.* **2012**, *44*, 386–396. [CrossRef]
64. Reinhart, C.F.; Walkenhorst, O. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy Build.* **2001**, *33*, 683–697. [CrossRef]
65. Illuminating Engineering Society of North America. *Daylight Metrics Committee. Approved Method: IES Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE)*; lluminating Engineering Society of North America: New York, NY, USA, 2012.
66. Nabil, A.; Mardaljevic, J. Useful daylight illuminance: A new paradigm for assessing daylight in buildings. *Light. Res. Technol.* **2005**, *37*, 41–59. [CrossRef]
67. Konis, K. A novel circadian daylight metric for building design and evaluation. *Build. Environ.* **2017**, *113*, 22–38. [CrossRef]
68. Clotilde, P.; Eugenia, S.M.V.; Mariëlle, A.; Marilyne, A. A conceptual simulation workflow to guide design decisions regarding the effects of daylight on occupants' alertness. *J. Phys. Conf. Ser.* **2021**, *2042*, 012116. [CrossRef]