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A systematic literature review: Building window's influence on indoor circadian health

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ABSTRACT

Light has been shown to have a non-visual impact on the biological aspects of human health, particularly on circadian rhythms. Building windows are a potential means of regulating daylight conditions for circadian health and well-being. As a result of advancements in window and glazing technologies and variations in outdoor solar/sky conditions, understanding daylight's spectral characteristics, which pass through building window systems, is complex. Therefore, a systematic review and summary of the knowledge and evidence available regarding windows' impact on human circadian health is necessary. This study provides an overview of research in this domain, compares approaches and evaluation metrics, and underscores the importance of window parameters' influence on circadian health. Published studies available on various online databases since 2012 were evaluated. The findings of this study define a holistic approach to the melanopic performance of windows and provide an overview of current knowledge regarding the effect of windows on circadian health. Additionally, this work identifies future research directions based on the studies reviewed. This research contributes to the growing body of knowledge on the impact of windows on circadian health, which has implications for the design and construction of buildings in ways that support indoor human health and well-being from the circadian light adequacy perspective.

1. Introduction

In response to light, the human body reacts both visually and non-visually. These responses are due to the light perception occurring in the retina. In the retina, rods, cones, and identification of photosensitive retinal ganglion cells (ipRGCs) are photoreceptors that detect and respond to photon signals. Visual responses are controlled by rods and cones. According to Ref. [1], besides their morphological differences, rods and cones respond to light differently, causing different visual characteristics of the eye in darkness and brightness. The cooperation between the brain's primary visual cortex and these photoreceptors allows us to perceive comfort from a visual aspect that influences human performance and well-being. The visual response is a well-recognized topic subjected to various assessments. For example, the effect of illuminance on the occupant's learning was discussed in Refs. [2,3], and its effect on work performance was studied in Refs. [4,5]. In addition, studies [6,7], and [8], respectively, have demonstrated a positive correlation between lighting and satisfaction, mood, and patients' healing duration. In addition to illuminance, the impact of window view has been discussed in several studies. As reported by Ref. [9], the amount of natural view positively correlates with employee job satisfaction and restoration. As well as the impact of a window view in the office [10,11], investigated the impact of a window view on patients' hospital recovery and stress and mental fatigue at a school, respectively. Discomfort caused by glare is another essential consideration in studies of visual comfort. According to Ref. [12], an individual with an early chronotype is more tolerant of glare.

Regarding the non-visual response, beyond the rods and cones, it has recently been recognized that ipRGCs cause non-visual responses. To activate the non-visual response, ipRGCs require a relatively extended duration with a high level of light exposure [13]. Non-visual responses occur by conversion of photon signals into neural signals, including behavioral rhythmicity, ocular immunity privilege gating, and pupillary responsiveness ([14,15]). Circadian lighting that stimulates the non-visual response has been defined by Ref. [16] as spectrally-opponent mechanisms that trigger synaptic connections between the ipRGCs and the distal retina. By synchronizing with the 24-h cycle of sunrise and sunset, the human biological rhythm, called the circadian rhythm, provides a healthy pattern for humans. As a result of contact with light with a power distribution peak at a shorter wavelength [17], this synchrony is regulated by the bovine pineal gland in

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Nomenclature

aca	circadian action factor (unitless)
CL_A	circadian light
CER	circadian efficacy ratio
CS	circadian stimulus (unitless)
E_v	virtical (photopic) illuminance (Lux)
EC glazing	electrochromic glazing
EML	equivalent melanopic lux (m_Lux)
f	Spatial Distribution of Circadian Light Exposure, according to the visual field, ranges 0.5-2
LER	light exposure ratio
$M(\lambda)$	melanopic luminous sensitivity function
m-EDI $\_E_{v,mel}^{D65}$	melanopic equivalent daylight illuminance
M/P	melanopic-photopic ratio
$S(\lambda)$	spectral power distribution of light sources
SPD	spectral power distribution
t	Time in Hours, ranging from 0.5 to 3
Tvis	visible transmittance
$V(\lambda)$	photopic luminous sensitivity function
WWR	window-to-wall ratio
$\gamma_{mel,v}^{D65}$	ratio of a test source's melanopic efficacy of luminous radiation to the melanopic efficacy of luminous radiation of D65 (unitless)
$\varphi_{n(lamp)}$	normalized spectral power distribution of the light source (unitless)
$\varphi_{n(D65)}$	normalized spectral power distribution of the reference illuminant (D65) (unitless)

suprachiasmatic nuclei (SCN) that release the hormone melatonin [18]. Directly controlling the sleep-wake cycle, the circadian rhythm also indirectly impacts core body temperature and blood pressure. A disruption in this cycle can lead to various health problems, including diabetes, cardiovascular disease, and even cancer [19]. Therefore, lighting quality is critical to human health.

Sociological studies have indicated that 87 % of Americans spend their time indoors [20], an amount that likely has increased due to the pandemic. Appropriate indoor circadian lighting is crucial, which dynamically and time-dependently adjusts the spectral power distribution (SPD) and occupants' light exposure adaptation, considering their previous exposure history [21]. Regarding the time of exposure, Andersen discussed the effects of exposure to daylight at different times in Ref. [22]. While light exposure during the late day is a reason for the phase delay, exposure during the early day makes the phase advance. Furthermore, light exposure during the middle of the day does not impact the phase shift, although it impacts alertness. Regarding the illuminance intensity, there is a linear relation between light intensity and the non-visual effect of light, and it is normalized between 0 and 100% [23].

One of the components critical to creating a healthy indoor environment is lighting, consisting of both artificial and daylighting conditions [24]. In this context, artificial lighting has primarily been explored to identify adequate indoor lighting capable of satisfying well-being thresholds because of the ease of manipulating lighting properties within experimental setups. For instance Ref. [25], examined how bipolar disorder was affected by electric lighting, both during the day and at night. A review conducted in Ref. [26] found that bright ambient light with intense circadian stimulation may mitigate depressive symptoms and agitation in people with dementia. Alternatively [27], investigated the impact of widespread LED use on retinal circadian cycles. Despite these [28], demonstrated that morning is the optimal time for triggering the circadian response to light. Furthermore [29], proved that exposure to electric light does not produce results identical to daylight from a circadian rhythm perspective. As assessed in this study, electric light shifts melatonin onset and offset to 2 h later than daylight, meaning that when melatonin onset occurs close to sunset, its offset happens before wakeup and after sunrise. However, with electric light, melatonin onset occurs 2 h before the sleep hour and offsets after waking. Consequently, although electrical light is beneficial for providing an acceptable indoor visual environment, it does not substitute for daylight regarding circadian health.

Furthermore, because daylight varies in intensity, color, and direction during the day and with the different seasons, it brings more complexity when studying the influence of architectural daylighting on circadian health. In Ref. [30], the authors assessed the transmitted daylight intensity of a classroom in Spain from a circadian health perspective, arguing that LED lighting should be used as a supplement to indoor lighting to provide a healthier indoor environment for students. The glazing system can also alter input daylight from luminosity and temporal perspectives, following optical and morphological characteristics [31]. Significantly, the optical properties of the glazing system (which specify the spectral transmittance and reflectance of a window) influence the SPD of daylight. Since the maximum sensitivity wavelength for circadian light is blue wavelengths (~446–479 nm) [32], the types of window systems that feature the required optical properties for transmitting the corresponding SPD must be considered [28]. Aside from the window system's optical properties, another factor influencing transmitted light is its morphological aspects.

Due to the discussed complexities and the close relationship between daylighting conditions mediated by architectural window and glazing systems and the circadian health of occupants, the importance of studying such window systems has been well recognized in the domain. In recent years, a significant body of research has explored the impact of windows on circadian health, but only limited attempts have been made to review and synthesize previous studies or collect evidence on the causal relationship between a window system and indoor circadian health. There have been some relevant review studies about circadian lighting and health; however, these have focused primarily on artificial and daylight, underestimating the influence of windows on circadian health. Table 1 lists the summary of these review studies. As listed in Table 1 [33], is the only study that focused on the window; however, it did not cover all effective window characteristics on circadian light. This

Table 1
Highlights of published review studies on circadian light.

Reference	Highlights	Window inclusion in study
[33]	Impact of architectural characteristics, such as window area, surface reflectance, and window orientation on circadian lighting design.	Yes
[34]	A systematic review of the impact of light's intensity, SPD, duration, and time of exposure to light on the circadian rhythm.	No
[35]	Non-visual effect of light's color temperature and intensity and monochromatic light's effect on human physiology.	No
[36]	Reviewing the impact of the light's intensity, exposure duration, phase, and SPD of light on the circadian rhythm.	No
[37]	The non-visual impact of light on psychological and physiological responses.	No
[38]	Reviewing the workflow for simulating the non-visual impact of light.	No
[39]	Association between Daylight Saving Time (DST) and acute myocardial infarction (AMI), which may be caused bythe disruption of the circadian rhythm.	No

study's primary focus is on the windows' morphological properties. Besides, studies [34–36], and [37] provided a general perspective of light's impact on the circadian cycle without emphasizing the role of the window. Alternatively [38], reviewed only the simulation of the non-visual effects of light in a built environment. In Ref. [39], a more detailed association between daylight-saving time and circadian rhythm and acute myocardial infarction was reviewed. Therefore, a comprehensive review study focusing on the impact of daylight transmitted through a window on the circadian cycle must be included.

Moreover, driven by the desire to save energy in building environments, a variety of emerging window technologies (e.g., those with spectrally selective films, low emissivity coatings, smart glazing systems, and attachments) have increasingly been designed, examined, and developed in recent years [40,41], also contributing to the impact on circadian health. As a result of these increased needs, by synthesizing the studies published in the last decade in peer-reviewed journals, this literature review provides an in-depth understanding of and evidence regarding how and to what extent window systems affect transmitted daylight-related circadian levels and occupants' circadian health. This work proposes the following significant contributions. This study aims to examine the optical and morphological characteristics of windows that have been reported as evaluation variables or as constant experiment parameters in previous studies. As a result of research focusing exclusively on circadian health, this project was inspired. This study aims to assess variables' effect on circadian light transmission and its implications for human health. Moreover, this study identifies issues and shortages related to implementing a standardized scale and metric for evaluating circadian light transmission.

2. Theory

2.1. Circadian light and health impacts

Russell Foster was the first to propose the concept of another photoreceptor's existence in the eye that, unlike rods and cones, does not contribute to image formation. Based on Foster's experiments [42], mice's eyes showed normal circadian responses to light despite the absence of both rods and cones; in 2002, a study conducted by Berson [17] described the existence of ipRGCs as well as their function, which exhibit lower sensitivity to light and a sluggish response that takes more than a minute to occur. While ipRGCs have their particular light-sensitive pigment named melanopsin, they could also be triggered by the light signal initiated by the rod and cone cells and sent back to bipolar cells that eventually reach the ipRGCs [43]. According to the time and period of light exposure, human biological responses can have positive or negative, acute or delayed, or long-term effects [44]. Based on the length, it is possible to categorize such rhythms into one of four categories: ultradian (<24 h), circadian (24 h), infradian (>24 h), or circannual (approximately one year) [45]. In response to the duration of light exposure, the human body shows specific psychological and physiological reactions that can be classified into three categories: acute, delayed, or long-term. Houser et al. [46] listed some of these reactions by their time course, as shown in Table 2.

Table 2
Body's Physiological Responses based on the Time Course of Light Exposure.

Time course	Psychological response
Acute (seconds or minutes)	• Variations in pupil size Acute melatonin suppression Luminance adaptation Short-term chromatic adaptation
Delayed (hours, days, or weeks)	Circadian phase shift Sleep quality Long-term chromatic adaptation
Long-term (months or years)	Stress Poor health Seasonal affective disorder Depression

Table 2 shows that an acute response does not affect the circadian rhythm. At the same time, the rest, caused by the consistency of insufficient lighting conditions, are part of circadian health and should be subjected to further study. The importance of indoor lighting for health is undeniable based on the daily period spent indoors. Accordingly, different metrics have been recommended to measure the non-visual impact of light on circadian health and are also often used in studies in this domain. A summary of these metrics is provided in Table 3. As discussed in Ref. [47], EML is a non-visual light intensity indicator often measured on a vertical surface to represent the human eye position. EML is computed by normalizing the SPD of a light source at different wavelengths. The *m*-EDI, also known as $E_{v,mel}^{D65}$, indicates the illuminance level of daylight D65, which is a standardized lighting condition representing a specific type of daylight with correlated color temperature (CCT), approximately 6500 K, which gives the same melanopic irradiance as the light source [46]. By multiplying the photopic illuminance by the melanopic daylight efficacy ratio, the *m*-EDI might be computed. Based on melatonin suppression, the CS metric defines the circadian system's absolute sensitivity according to the retinal light stimulus [48]. CS is defined according to circadian lighting, which is irradiance at the cornea weighted to represent the spectral sensitivity of the human circadian system as evaluated by acute melatonin suppression after an hour of exposure to light [49]. Circadian action factor (a_{cv}) could be calculated by the division of circadian luminous efficacy of radiation (CER) to luminous efficacy of radiation (LER) [50]. M/P is the melanopic illuminance (EML) to photopic illuminance (lux) ratio, which is measured at eye level [51]. The melatonin suppression index (MSI) is used to evaluate the impact of the light source on suppressing melatonin

Table 3
Summary of circadian metrics.

Metrics	Equation	Threshold
EML	$EML = E_v \times \frac{\int S(\lambda)M(\lambda)d\lambda}{\int S(\lambda)V(\lambda)d\lambda} \times$ 1.218 OR $EML \approx m - EDI \times 1.103$	**Work area** = including the daylight, minimum 200 EML in at least 75 % of workstations with cornea height of 120 cm, between 9:00 to 13:00. **Living area** = during the daytime, minimum 200 within the cornea height of 120 cm facing wall; during nighttime, not exciting 50 EML within the cornea height of 76 cm. **Breakrooms** = Minimum of 250, with a cornea height of 120 cm. **Learning area** = including the daylight, minimum 125 EML in at least 75 % of desks with cornea height of 120 cm [53]
m-EDI	$E_{v,mel}^{D65} = E_v \times \gamma_{mel,v}^{D65}$	**During daytime** = Minimum 218 lux, between 09:00 to 13:00 [54] **During nighttime** = Maximum of 10 Lux 3 h before bedtime, and 1 Lux during the night [55]
CS	$CS = 0.7 - \frac{0.7}{1 + \left(\frac{CL_{A,2.0} \times t \times f}{355.7}\right)^{1.1026}}$	CS of 0.3 or greater for an hour in the morning hours [56]
a_{cv}	$CAF = \frac{CER}{LER} = \frac{683\,\frac{\int C(\lambda)S(\lambda)d\lambda}{\int S(\lambda)d\lambda}}{683\,\frac{\int V(\lambda)S(\lambda)d\lambda}{\int S(\lambda)d\lambda}}$	-
M/P	$\frac{M}{P} = \frac{\int S(\lambda)M(\lambda)d\lambda}{\int S(\lambda)V(\lambda)d\lambda}$	**During morning** = Greater than 0.9 for school and workplace **During afternoon** = less than 0.35 [57]
MSI	$MSI = \frac{\int_{380}^{730} \varphi_{n(lamp)}(\lambda)M(\lambda)d\lambda}{\int_{380}^{730} \varphi_{n(D65)}(\lambda)M(\lambda)d\lambda}$	-

in people [52].

2.2. Window performance and circadian health

Houser et al. [58] discussed that lighting could be adjusted independently by four variables: spatial pattern, light spectrum, light level, and temporal pattern. All these four variables unevenly impact the light stimulus entering the eye and contribute to the biological potency of circadian light. The spatial patterns could be considered the interior space impact on luminance distribution. Light spectrums focus on the lighting SPD and chromaticity; lighting level focuses on the light intensity; and finally, the temporal pattern and time and duration of exposure are effective parameters. Windows influence indoor circadian health through their ability to transmit level categories.

Fig. 1 presents a diagram of how windows mediate between varying incident daylight conditions and indoor circadian health. Generally, there are four nodes: daylight source, windows and glazing, interior configuration, and occupants. ***Node 1***. The daylight source can vary widely in terms of circadian light conditions. For instance, the light intensity and level differ between cloudy and clear skies and vary according to the seasonal solar position. By transmitting daylight through the windows (***Node 2***), incident daylight's SPD can be altered according to the window's optical and morphological properties. The geometric relationship between the window and daylight source is crucial in influencing the intensity and SPD of the incident daylight condition. Consider, for example, that north-facing windows may only receive the blue-dominated daylight generated by the sky dome without direct sunlight. Similarly, the shape, slat spacing, and materials of the window's attachments, such as overhangs and shades (static or dynamic), may frame the incident daylight conditions in different seasons and times of the day, further affecting the intensity and SPD of the incident daylight condition. Moreover, the optical properties of window and glazing systems are determinants of transmitted light. See the examples in Fig. 1b below. The two window systems have quite similar visible and solar transmittance but dramatically different SPD features. In particular, the visible transmittance range in the grey highlighted portion and the melanopic transmittance range in the blue highlighted portion are illustrative. Window A exhibits much higher melanopic transmission compared to Window B. As such, the full spectral characteristics of the window and glazing system must be taken into account in a circadian light analysis. ***Node 3*** refers to the interior space (and associated artificial lighting spectral features). The daylight transmitted through ***Node 2*** is subsequently influenced by the spatial and material features of the interior space, such as the depth of the room, spectral reflectance of interior surfaces, and other indoor furniture and spectrum-related settings. Last, occupants ***(Node 4)*** are the final recipients of indoor circadian lighting; therefore, human factors such as body posture, whether the person is seated or standing, and their head direction according to the window may influence the receipt of circadian light.

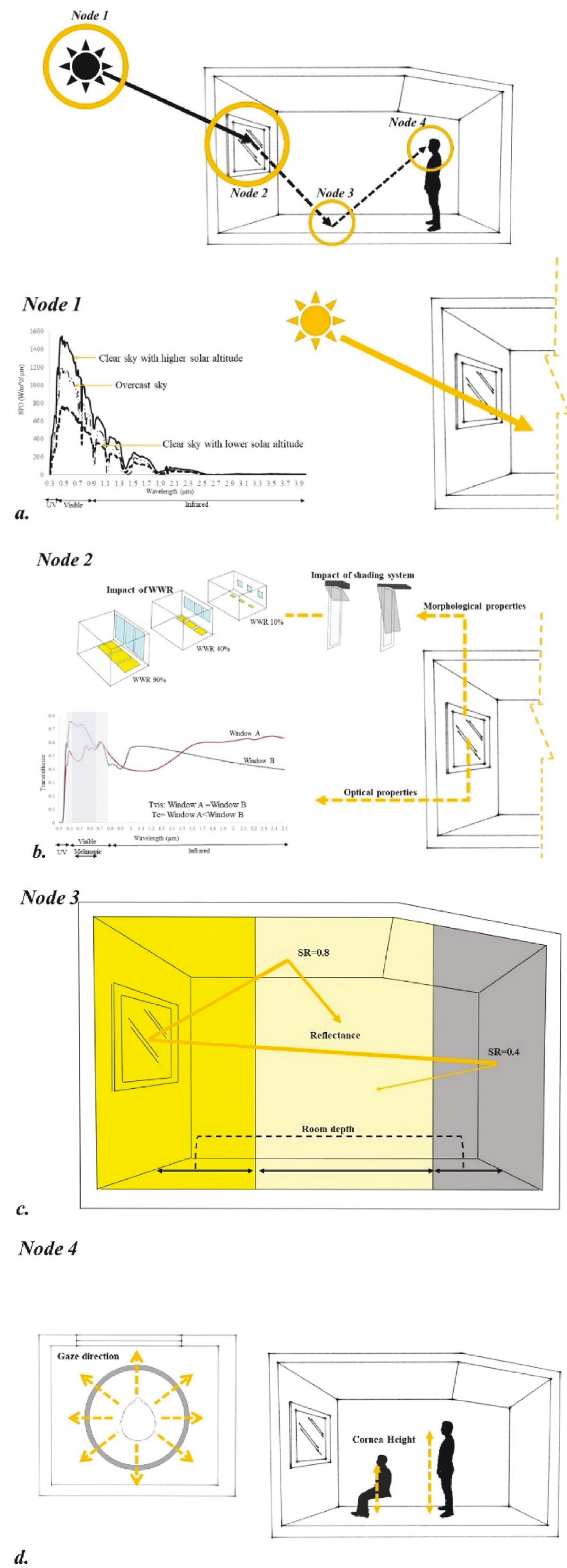

Fig. 1. Schematic view of factors affecting transmitted circadian daylight: a. Detailed view of Node 1, b. Detailed view of Node 2, c. Detailed view of Node 3, and d. Detailed view of Node 4.

3. Materials and method

3.1. Search engine

The following search engines were used to review the work on indoor daylight and circadian health: PubMed, Google Scholar, Science Direct, Scopus, Web of Science, and Semantic Scholar. The most recent search was conducted in February 2023. Only English-language studies were chosen. The works were filtered based on their titles and keywords. Table 4 lists the keywords used for the search.

The keywords were selected primarily based on similar studies covering this area's core information. Therefore, as presented in Table 4, the synonym words in each column are grouped and listed with the "OR" operator in the research query string. The groups of synonym words in three columns representing a core part of the research were linked by the "AND" operator. This is to guarantee that the coverage of the relevant

Table 4
Keywords and Phrases used for the Studies Search.

	'AND' operator		
'OR' operator	Light	Circadian	Window
	Illuminance	Non-visual effects	Glazing system
	Spectral power distribution	Melanopic response	Glass
	Circadian stimulus	Health	Aperture
	Equivalent melanopic lux	Non-image-forming effects	Optical properties
	Melanopic equivalent daylight illuminance	Diurnal rhythm	Glazing
	Circadian stimulus	Biological clock	Fenestration
	Daylight	Melatonin	
	Spectral power distribution	Core body temperature	

research is maximized in the results listed by the research engine.

3.2. Selection criteria and screening process

The literature search was conducted based on the Preferred Reporting Items for Systematic Reviews [59]. The search engines indicated above indexed 2983 studies, based on the keywords listed in Table 4. The following inclusion criteria were used to reduce the candidate studies.

1. Studies published in peer-reviewed journals.
2. Works published after 2012.
3. Inclusion of both window characteristics and circadian metrics.
4. Subjected light refers to the light transmitted through the window.
5. The impact of artificial light was kept off or constant during the research.

Commentaries, qualitative studies, expert opinions, editorials, and conference abstracts were excluded from the study. The list does not include studies in which the variable lighting source was electric lighting or the room opening for transmitting light was a skylight. The authors selected the research that met the criteria for selection. Fig. 2 illustrates the PRISMA flow chart for tracking the search and screening process.

A total of 2821 studies remained after duplicates were deleted from the index of 2983 studies. These were initially evaluated by reviewing

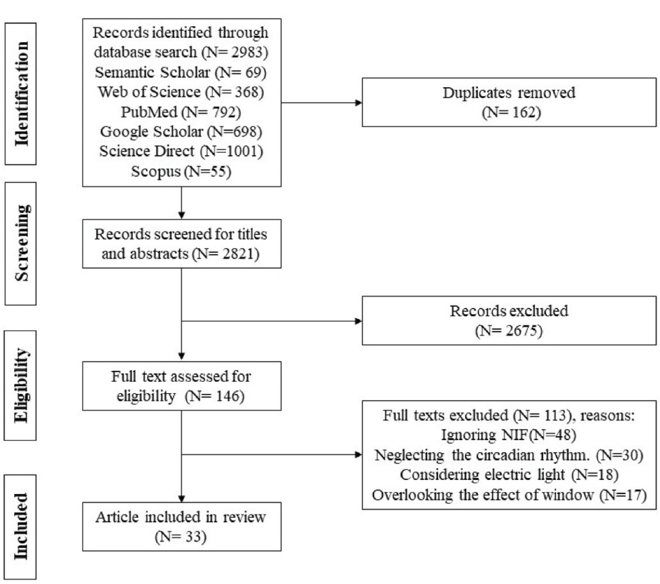

Fig. 2. PRISMA flow diagram.

the titles and abstracts, resulting in 146 works being selected. The factors that helped to reduce the number of studies included visual comfort or visual effect or glare, thermal comfort or heat stress, general daylighting benefits without focusing on optical window or glazing characteristics, and studies focusing only on electric lights. After reviewing the work's complete text for eligibility, 113 studies that did not meet the selection criteria were removed. This resulted in 33 studies being eligible for review.

3.3. Data extraction plan

One author conducted data extraction. A summary of the extracted data can be found in Table 5 in the Appendix section. According to Table 5, information regarding the research setting, including location, type of room, simulation software used in simulation-based studies, interior surface reflectance, and any constant optical or morphological characteristics of the windows, was derived from the analyses. The table also includes evaluation metrics and window properties, the studies' variables, and their corresponding results.

4. Results

4.1. Study characteristics

4.1.1. Study type

A total of 33 studies were identified in this review. Summaries can be found in Appendix Table 5. Twenty-one of these 33 works were simulation-based. Among them, nine were only simulation-based ([30,60,61,62,63,64,65,66,67]), while an experiment accompanied the remaining twelve. Nine of the twelve experiments were in situ measurements ([57,68–75]) and two were interventional human-subject studies ([76,77]). Beyond the nine studies describing in situ measurements, five studies were solely in situ measurements ([69–71,73,75]). The listed interventional human-subject studies were not the only studies in this category; an additional five studies were conducted according to this research type ([78–82]). Following are further details regarding the simulation-based and experimental settings employed.

4.1.2. Study location

A total of 30 different geographical locations were analyzed in the selected studies; a few considered multiple locations. For example [61,83], assessed experiments at two different locations, whereas [62,76] evaluated experiments at three and five locations, respectively. However, some locations were selected repeatedly. Fig. 3 shows the areas chosen and the frequency with which they were considered. From the southern hemisphere, only one location was evaluated [74]; from the northern hemisphere, experiments covered a wide range of latitudes between 13.35°N and 64.58°N.

4.1.3. Spaces analyzed

The studies used various settings, including living rooms, classrooms, healthcare facilities, offices, and test cells. The most common space used was the office, which appeared in 14 studies. The office rooms were either open-plan ([56,60,66,84]) or private ([57,67,72,78,80–83,85]). Seven studies were conducted in "test cells" ([63,65,69,70,77,86,87]), representing the second most commonly used space in this body of research. Healthcare centers were the third most frequently used, appearing in six of 33 studies. Two of these six were carried out in a patient room at a hospital ([61,68]). The rest were conducted in dementia care facilities. For the experiments in dementia care facilities, two types of space were chosen: either a bedroom ([71,74]) or a living/activity room ([73,88]). The following five studies used a classroom as the area of assessment ([30,62,75,76,89]). The only study conducted in a residential unit was [79].

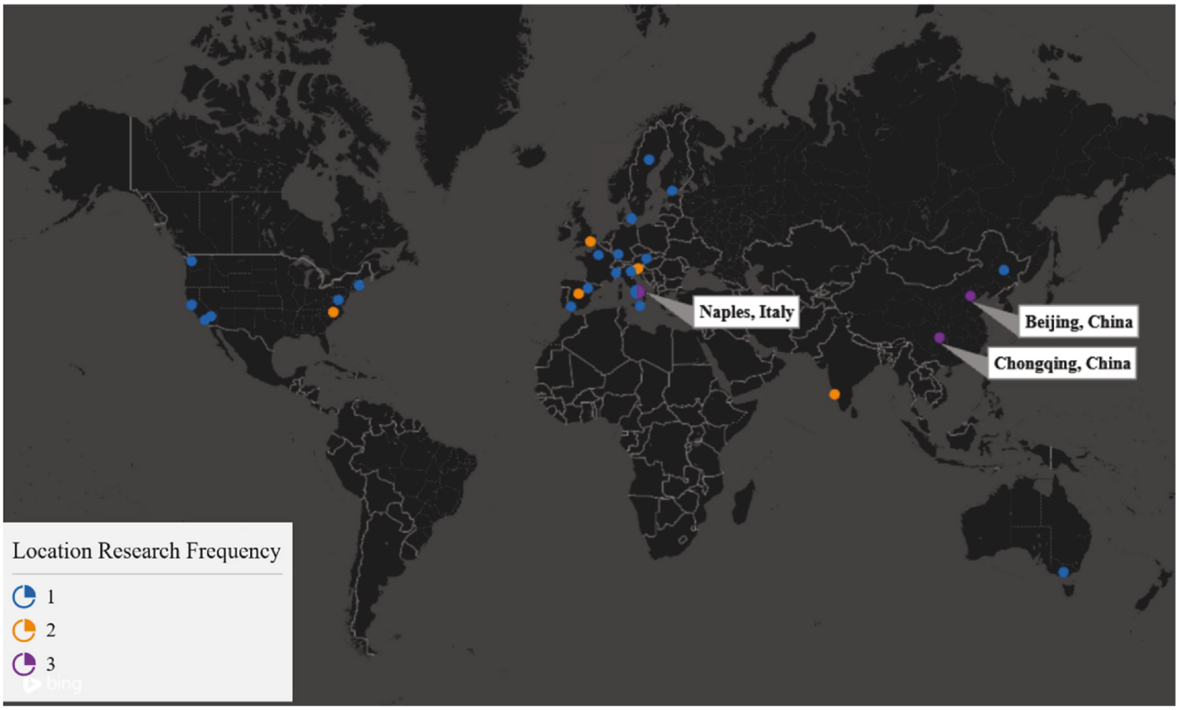

Fig. 3. Locations of studies and how often they were considered.

4.2. Characteristics according to study type

Certain characteristics emerged in accordance with the study type. The following section summarizes characteristics based on the type of study.

4.2.1. Simulation-based studies

4.2.1.1. Study design. In most simulations, fundamental parameters regarding surface spectral properties were set as the model's default. The parameters involved were window visible transmittance and interior surface reflectance. A detailed discussion of window visible transmittance appears in the Study Variables section. The assigned surface reflectance is discussed here. Sixteen studies assigned a value for interior surface reflectance. The six that excluded interior surface reflectance were ([74,76,77,84,85,88]). Mainly, the reflectance reported varied according to the type of surface. The floor generally had a lower reflectance value relative to other surfaces; if the interior surface reflectance was not a study variable, the range for the floor was between 0.2 and 0.4.

Conversely, the walls and ceiling had approximately the same reflectance values in each study. The range considered for the interior surface if the surface reflectance was not a study variable was between 0.65 and 0.90. For more precise simulation, the reflectance values of the interior furnishings were also reported in ([57,68]).

4.2.1.2. Software. Different software packages were used for simulation-based research. Fig. 4 summarizes the final end-user software interface according to its popularity. LARK, Ladybug, and Honeybee are plugins for Rhinoceros Grasshopper. LARK enables spectral lighting simulation and analysis, while the Ladybug and Honeybee plugins add RADIANCE engine functionality to Rhinoceros. ALFA is an interface embedded in Rhinoceros for the spectral analysis of light. Fig. 4 shows that ALFA and DAYSIM were the most popular methods for circadian light simulation, and both simulation tools utilize RADIANCE as the underlying engine for their daylighting simulations.

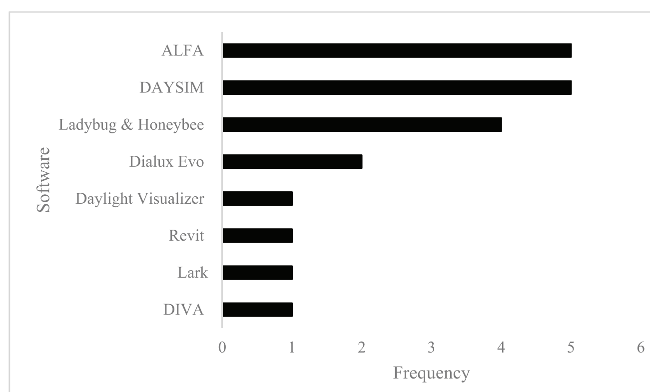

Fig. 4. Frequency of end-user software interface used for simulation.

4.2.2. Interventional human subject studies

4.2.2.1. Sample. Study samples ranged from 11 to 542 participants. Only one [76] with 542 participants contained a large number of participants. This was due to the breadth of the study, which examined students in eight classrooms in five different cities in Italy. By excluding this study, the range of samples was reduced to between 11 and 30. In all cases, except for [77], both males and females were considered. It should be noted that the average participant age, after excluding [78,79], and [82] (which contained a broad range of ages), was close to 23 years. Only one study [79] evaluated participants' sleep duration before the experiment. This was accomplished using the Munich Chronotype Questionnaire.

4.2.2.2. Questionnaire. Surveys were administered to assess sleep quality, mental health, and physical well-being. To measure sleep quality, the Karolinska Sleepiness Scale (KSS) and Pittsburgh Sleep Quality Index (PSQI) were used [81]. In Refs. [79,81], the Positive and Negative Affect Schedules (PANAS) were employed to measure mood and emotional health. At the same time [78], used the Patient-Reported Outcome Measurement Information System (PROMIS) to analyze participants' mental health. According to Ref. [80], the Visual Analogue Scale was used to measure occupant satisfaction with the light's visual and non-visual aspects.

4.3. Study Variables

4.3.1. Visible transmittance

Eleven studies considered Tvis as the variable in their experiments ([57,66,69,70,78–81,81,82,87]). Five used smart glazing systems, including electrochromic glazing ([66,78,79,82]) and polymer-dispersed liquid crystal (PDLC) windows [87], both of which dynamically switch the Tvis. The rest of the studies focused on applying colored films to clear glass ([70,80]) or glass with different colors or levels of visible transmittance ([57,69,72,81]), which provided different Tvis values.

4.3.2. Gaze direction

Fourteen studies focused on this variable. Six ([60,61,65,66,84,88]) considered a 360-degree circular gaze direction with 45-degree step intervals. According to these studies, this step interval was the smallest possible for evaluating the effect of gaze direction on the horizontal plane. In Ref. [30], the same interval was used but within 90° of the perpendicular and parallel view direction to the window. The 90-degree step intervals were the second rotation interval considered in ([69,71, 73]), resulting in four occupant view directions (one perpendicular to the window, two reverse-parallel to the window, and one a backward view). Three gaze directions were considered in Ref. [86]: two parallel and one backward. In ([56,57]), the same situation was repeated; however, the view was perpendicular rather than backward. A unique aspect of [75] was its examination of variations in gaze direction on the vertical axis. The subject of this study changed gaze direction to three positions on the vertical plane, including a straight view, a 15-degree tilt, and a 45-degree tilt. On the horizontal plane, the gaze direction was parallel to the window.

4.3.3. Window-to-wall ratio

In total, eight studies considered this factor as a study variable. Only three evaluated this parameter alone ([60,76,77]). The correlation between interior surface reflectance and WWR and its effect on circadian light was assessed in ([61–63,89]). By taking WWR and interior surface reflectance into account, two equations were proposed for vertical illumination ([63,89]). Furthermore [64], evaluated the impact of WWR and orientation on the satisfactory performance of interior daylighting in response to circadian stimulation.

4.3.4. Distance from window

Eighteen studies examined the impact of distance from the window on circadian light. Eight ([30,56,57,60,69,74,75,88]) focused on this variable alone. Of those ([61,64]), evaluated the effect of this variable in addition to WWR. In Ref. [83], the impacts of WWR, window orientation, and distance from the window were all evaluated. Moreover, the impacts of distance from the window and window orientation were assessed in Ref. [84]. The influence of the distance from the window was determined by correlating it with gaze directions, as indicated in ([65, 66,71,86]). [62] examined the effects of distance from the window and interior surface reflection on interior circadian light. Finally, the impacts of sky type and distance from the window were evaluated in Ref. [68].

4.3.5. Window orientation

In total, 13 studies focused on the impact of window orientation on circadian light. In ([30,56,66,68,77,83]), only the effect of orientation was assessed. The impact of orientation on different seasons was evaluated in ([67,76,85]). The impact of orientation and WWR was discussed in ([62,64]); moreover, in Ref. [74], the window ratio considered was the window-to-floor ratio. Finally, in Ref. [65], the influence of window orientation on circadian light was examined in conjunction with the interior surface's solar reflectance.

4.3.6. Shading

Only three studies analyzed the shading system as part of the glazing system and evaluated its impact on circadian light. In Ref. [86], two types of shading systems, "25 mm-wide matte white slats with 20 mm spacing at 25°, adjusted and lowered," and "matte grey specular louvers with reflective film put on a concave upper louver" were implemented in double-glazed insulated units. A continuous overhang with a depth of 1.4 *m* and a horizontal blind with a depth of 10 cm and spacing of 9.5 cm were evaluated and compared to an EC glazing system in two tint states [66]. In Ref. [84], a Venetian blind was used as the shading system.

4.3.7. Elevation metrics

These studies employed 14 measures, six of which were circadian metrics. CS was one of the most widely used evaluation metrics, with 15 studies employing it ([56,61,62,64,70,72,78–82,84,85,87,89]). EML was the second most commonly used metric ([30,56,57,60,66,68,69,71, 72,74,76,82,83]). The *m*-EDI and M/P ratios were assessed in ([30,67, 73]) and ([57,69,71]), respectively. Only [75,77] utilized a_{cv} and the Melatonin Suppression Index, respectively. The details of the study measures and frequency of use in percentages are listed in Fig. 5.

4.4. Findings

4.4.1. Windows and circadian light

4.4.1.1. Visible transmittance and circadian light. Four of the 11 studies that focused on visible transmittance used EC glazing in their evaluation ([78,79,82]). provided EC comparison data for glazings with similar Tvis values, but opaque blinds covered three-fourths of the area. According to ([78,82]), CS values over 0.3 were found, indicating that EC was more effective at letting in circadian daylight than a window with blinds. In Ref. [79], while the reported CS for EC glazing was below the threshold, relative to a window with blinds, it was higher. Conversely, comparing EC with a shading system showed that the shading system was more efficient at letting in circadian daylight. As reported in Ref. [66], EC reduced the penetration of circadian light EML >240 by 15.3 *m* when the Tvis was 0.18, and the reduced penetration length increased to 16.8 *m* when the Tvis reached 0.06. In Ref. [87], the transparency status switch in PDLC glazing did not prevent circadian light from entering the building. During the experiment, the CS value was above 0.4. In Ref. [57], thermochromic glazing (TC) coating was compared with clear and blue-tinted glass, resulting in 32%, 18%, and

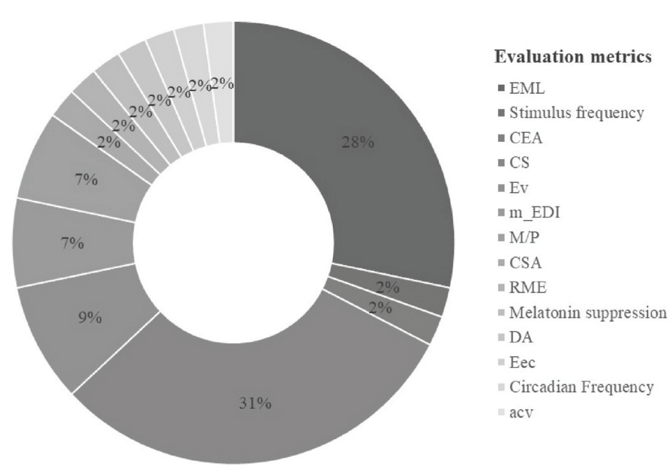

Fig. 5. Frequency of metric use.

7% of the room areas being below the M/P ratio of 0.9 when the glazing was thermochromic glazing, clear window, and blue-tinted glass, respectively. Glazings with different colors and various Tvis values were subjected to assessment in ([70,72,80,81]).[70] found no linear correlation between the visible transmittance and CS value, similar to the results of other studies, as some glazings with high visible transmittance are inefficient at meeting the threshold of circadian light. In Ref. [80], while all tinted glass effectively provided a CS above 0.3, green-tinted glass with a Tvis of 0.68 had the best performance, providing a CS of 0.487 at a location within 1.8 *m* of the window. According to Ref. [81], red-, grey-, and yellow-tinted glass failed to provide a CS above 0.3 within 1.8 *m* of a window before 9:15, 9:40, and 9:50 a.m., respectively. Furthermore, dark blue glazing with a Tvis of 0.54 failed to meet the threshold throughout the experiment day. [72], which evaluated the combination of tinted glass with colored walls of different reflectance values, found that double-pane glazing with one clear and one low-e coated glass pane with a blue-colored wall with 0.595 reflectance was best at achieving the required CS. Finally [69], evaluated two types of glass with Tvis values of 0.39 and 0.7. The window with a higher Tvis had an M/P ratio above 1, while the one with a Tvis of 0.39 was below 0.4.

4.4.1.2. Gaze direction and circadian light. According to the 14 studies focused on gaze direction, gazing perpendicular to a window provided the most significant exposure to circadian light. The impact of gaze direction and distance from the window was examined in four studies ([66,69,71,86]). Within 2.3 *m* of the window, if the gaze direction was switched from perpendicular to parallel, the EML value when facing parallel was 0.24 times the value of a gaze towards the window [69]. When the distance was increased from 2.3 *m* to 4.1 *m*, the EML of the parallel gaze direction was 0.35 times that of the perpendicular gaze direction. Between 2.3 *m* and 4.1 *m*, the EML ratios for backward and perpendicular gaze directions were 0.14 and 0.61, respectively. In this way, the difference in exposure to circadian light decreased as the distance from the window increased. When the distance from the window increased, the perpendicular gaze direction had a greater impact than the parallel and backward gazes [71]. By moving from 3 *m* to 5 *m*, the EML ratios from 3 *m* to 5 *m* for perpendicular, parallel, and backward gaze directions were 0.54, 0.7, and 0.75, respectively. According to Ref. [86], the circadian weighted irradiance in the parallel gaze direction close to the window and perpendicular gaze direction when the distance from the window was 2 *m* were the same: 0.4 W/m^2. The depth of regions with satisfactory EML levels was reported in Ref. [66]: 21 *m*, 12 *m*, and 7 *m* for the perpendicular, parallel, and backward gaze directions, respectively. [73] investigated how gaze direction impacted circadian light exposure by season; the results showed that gaze direction was most effective during the summer, whereas it did not have as much impact on exposure to circadian light during the winter. The only research that evaluated the parallel gaze direction for all window orientations was [56]. According to this study, for north-, east-, south-, and west-facing windows, the maximum levels of CS in the parallel gaze direction were from gazing towards the west, south, east, and north, respectively. Finally, the only study that focused on variations in gaze direction along the vertical axis was [75]; based on that work, tilting the head downward caused the level of melatonin suppression to decrease.

4.4.1.3. Window-to-wall ratio and circadian light. Based on all published studies, it was established that increasing WWR increases circadian light to a sufficient level. The impact of WWR, when combined with interior surface reflectance, has been investigated in two studies ([63,89]). Based on these, interior surface reflectance was found to have a substitutive effect on circadian light relative to WWR; in addition, it is energy efficient. Window orientation was another variable evaluated. In general, as reported in ([61,62,64,76]), north-facing windows require higher WWR than south-facing windows to provide sufficient circadian light [83]. also evaluated the impact of orientation and WWR on circadian light. In this research, the effectiveness of these two variables was scaled by the electric light used to provide the required level of circadian light, and the comparison was between north- and east-facing glazing; increasing the WWR reduces electrical energy use for lighting, but this effect will vary from city to city.

4.4.1.4. Window distance and circadian light. The impact of distance from a window has been widely discussed in the literature. It has mostly been evaluated along with other variables, such as gaze direction and window orientation (discussed in their respective sections). Increasing the distance from the window decreases the sufficiency of circadian light. In Ref. [56], a distance further than 4.5 *m* from the window did not provide a CS above 0.3, while in Ref. [88], within 2.3 *m* from the window showed an average EML of 33.6. [57] evaluated the increment of distance from the window and its impact on the average deficient occasion, finding that the number of deficient occasions increased by 120 % at a distance of 3.5 *m* from the window and by 200 % at 5.7 *m* from the window, as compared to the number of deficient occasions at a distance of 1.3 m.

4.4.1.5. Window orientation and circadian light. An evaluation of the effects of window orientation on circadian light was offered in 13 studies. [68] considered the impact of seasonal variation and sky type on window orientation, finding that the penetration of circadian light through a north-facing window was not influenced as much by sky-type changes as was light through a south-facing window. According to Ref. [30], the worst cases were detected in the southwest and northwest directions; this research compared the southwest, northwest, southeast, and northeast directions. The impact of surface reflectance and window orientation on circadian light was evaluated in Ref. [65]; as a result of raising the surface reflectance from 0.2 to 0.8, daylight autonomy for a room with south-facing windows increased from 26.4 % to 41.5 %. However, the enhancement was from 22.5 % to 72.5 % for a room with a north-facing window. [62] investigated the impacts of WWR and window orientation, finding that for a room with a north-facing window, a larger WWR would be required to produce the same level of CS as a room with a south-facing window.

4.4.1.6. Shading system and circadian light. Compared with other parameters, little attention has been paid to the influence of shading systems on circadian light. This parameter has been the subject of only three studies. [86] compared the performance of Venetian Blinds (VB) and Optical Louver Systems (OLS), reporting that while VB provided higher illuminance during the day, the circadian weighted irradiance for Optical Louver Systems (as compared to Venetian Blinds) was higher between 11:00 and 12:00. This means that the circadian weighted light was not proportional to the illumination. [66] found that as long as the shading system did not substantially disrupt the sky view from the window, it would not interfere with circadian rhythms. Additionally, according to Ref. [83], which discusses a window's visual, energy, and non-visual performance indoors, when daylight illuminance at a distance of 0.75 *m* away from the window and above ground level exceeds 2000 lx, the blinds of lower windows are often lowered, increasing the electricity consumed by LED light to fulfill both visual and non-visual light-related needs.

4.4.2. Windows and circadian health

4.4.2.1. Sleep quality. There were seven "interventional human subjects studies," five of which focused on participants' sleep. The results of [78] indicated a significant impact of window type on sleep disturbance and sleep-related impairment. Using the normalized Patient-Reported Outcome Measurement Information System (PROMIS) T-score, it was evident that EC glazing was 0.9 times more likely to cause sleep disturbances than a window with blinds (p-value = 0.036). Regarding sleep-related impairment, the effectiveness of EC glazing was 0.87 times greater than a window with blinds (p-value = 0.049). The experiment condition described in Ref. [78] was roughly repeated in Ref. [79]; however, broader aspects of health were evaluated. In accordance with the factor analysis determined by the 20 Positive and Negative Affect Schedules (PANAS), EC glazing was 200 % more effective than a window with blinds with regards to controlling extrinsic positive emotions, and "Alert," one of the items on the 20 Positive and Negative Affect Schedules (PANAS), had a high loading coefficient. [80] found a significant correlation between alertness, window color, and time of day in their ANOVA test. In Ref. [81], which conducted a two-way ANOVA test to investigate the correlation between glazing color and participants' alertness, no significant main effect was found [F = 1.955, p-value = 0.07]. There was a significant correlation between time and alertness [F = 8.778, p-value = 0.07]. Finally [82], proved the impact of glazing on sleep duration. According to a fitted linear model, participants who used an office with EC had a 19.7-min increase in sleep duration. Compared to the baseline, people who used a room with blinds had a 14-min reduction in sleep duration.

4.4.2.2. Other health outcomes. While circadian health accounts for broader health aspects, none of the chosen studies focused on the correlation between windows and those health aspects. Only one study [80], which covered physical and emotional health, evaluated the impact of windows on well-being and mood. There is a significant correlation between window color and physical well-being and relaxation. According to Spearman's rho correlation between the CS responses to a Mood Questionnaire, there was no significant correlation between CS and mood [Spearman's rho = -0.01, p-value = 0.8].

5. Discussion

5.1. Circadian light metrics used in window-related circadian health studies

The chosen studies used various evaluation metrics to explore circadian light conditions. ***First***, as listed in Figs. 5 and 14 different metrics were used in total, and all were inherited from artificial or electrical lighting fields. While certain standards and authorities have defined metrics for circadian light, a universally accepted set of metrics has not been established across all authorities and scientific communities ([90,91]). Different authorities have developed and adopted various metrics, each focusing on specific aspects of this intricate system and driven by specific practical considerations. However, this heterogeneity of metrics use may result in inconsistencies and differences in the conclusions drawn about windows' influence on circadian health. Second, as shown in Fig. 5, some studies used photopic-based circadian light measurement systems instead of melanopic-based ones. This may have resulted in inaccurate or even erroneous conclusions due to the different peak sensitivity spectra and photopic and melanopic vision ranges. Accordingly, it is suggested that circadian health and window analyses should employ melanopic vision-focused metrics or basic radiometric quantities. ***Third***, among these metrics, the two most commonly used circadian light metrics in window-related circadian health studies are EML and CS. There is some doubt about the consistency of these two metrics, as mentioned in Ref. [56], in which both metrics are used to evaluate a room's circadian light performance. As reported by Zeng et al. while the circadian light conditions for two rooms were met according to the CS threshold, only one met the threshold based on the EML metric. Furthermore, that study found that at greater illuminance levels, EML values may be up to 75 % higher than CS values. This illustrates the discrepancy between the two metrics. Furthermore, the thresholds for these metrics vary according to occupant age [92], type of activity [53], and health status [93]. In most studies reviewed here, the evaluation threshold was a CS greater than 0.3 or EML equal to or greater than 240. ***Fourth***, similar to CS and EML, most circadian metrics were either reported as location-based and at eye level, the measured value for that specific point, or an average of the entire room, which may not adequately reflect transmitted circadian light for the entire area in a room. Despite the fact that in some studies, a metric such as the circadian frequency was proposed as a way to indicate the frequency of adequate circadian light on average for a given room during certain days in a week, the reported values did not offer accurate insights into the absolute value of circadian light and its adequacy.

Previous studies investigating the effects of windows on circadian health have used electrical/artificial lighting-based circadian lighting metrics. While some methods are popular and widely used, relying on a single technique or index in window-based circadian health studies is not recommended, as there is a discrepancy between the metrics and the threshold for reporting the results. For example, according to Ref. [72], there is a difference in the duration between indoor lighting which meets two CS and EML metrics. Additionally, according to Ref. [56], while both south- and west-facing windows meet the CS threshold, based on the EML, only the south-facing window does so. Even though this discrepancy is nonexistent in Ref. [72], it is significant in Ref. [56]. Moreover, these electrical/artificial lighting-based metrics are mostly calculated at eye level and for a specific location, failing to consider other spatial and temporal effects of natural daylight transmitted through windows on circadian rhythms. Therefore, it may be necessary to develop a new circadian light metric specifically for natural daylight entering through windows, considering the spatial distribution; this would address the gaps and discrepancies mentioned above.

5.2. Software or tools used for simulating circadian light through window systems

An appropriate simulation tool must recognize and accept the spectral characteristics of day/skylight sources, window and glazing components, and interior material surfaces to accommodate the complex optical features of window and glazing systems for circadian light analysis. Fig. 4 shows that ALFA and DAYSIM are the two most common simulation programs, while ALFA [94] and LARK [95] are the only spectral simulation programs capable of simulating circadian light through window systems. Among the selected research, LARK was not used as commonly as ALFA. This could be due to the user-friendly interface of ALFA's simulation software, as opposed to LARK, which requires knowledge of Radiance and Python programming. A comparison of LARK and ALFA was made in four studies ([96–99]). Accordingly, the simulation in ALFA was found to process faster than in LARK; the nine channels used for simulation in LARK took longer.

As reported in Ref. [96], the root mean square error for two reflective plaster materials under overcast and clear skies was smaller when simulated in LARK than in ALFA. However, ALFA presented a more precise outcome in a green environment under clear and overcast skies. Another study compared LARK and ALFA [97], concluding that Lark simulated ipRGC-influenced daylighting more accurately than ALFA and electric lighting was slightly more accurate. Furthermore, daylight exposure simulations over 6h in LARK and ALFA led to 9 % and 26 % errors, respectively, indicating that LARK was more precise. Two simulations, one three-channel, and one nine-channel, are available in LARK. In Ref. [98], the accuracy levels of these two methods were evaluated and compared to ALFA. The study concluded that the LARK nine-channel method provided the most accurate results relative to the ALFA and LARK three-channel options. [99] compared the simulations of the circadian effect of three luminaries on both platforms, LARK and ALFA, concluding that ALFA led to faster and more accurate output. The studies demonstrate that LARK is the best platform for simulating indoor daylighting and focusing on circadian effects, despite appearing only infrequently in the works selected for this literature review.

5.3. New fenestration indicator for circadian health

All studies in this research reported Tvis as a major property in terms of circadian light and health analysis, combined with qualitative descriptions such as glazing color ([70,72,80,81]). Based on the findings in those studies, there are several common features that window systems should possess to produce high levels of circadian light, including high visible transmittance (Tvis) and tinted glass with specific colors (i.e., green and blue). However, as discussed above, because photopic and melanopic vision have different sensitive spectral ranges and peaks, these references do not provide a consistent and quantitative assessment of a window's ability to produce circadian light. For instance, based on the window listed and its reported output, there can be glazing systems with low Tvis and high CS or EML [80]. Compared to commonly used indicators in the fenestration field, such as the U-factor, Tvis, and solar heat gain coefficient, a more accurate representation of transmitted circadian light can be achieved using radiometric quantities or melanopic transmittance, as adopted in Ref. [70]. However, it should be noted that the actual recipient level of circadian light is influenced by the glazing's optical properties and other elements, such as the daylight source, interior, and occupant, as the nodes illustrated in Section 2.2. Therefore, to develop a standardized indicator for circadian light, it is necessary to consider standardized boundary conditions that consider these different factors. It will be challenging for architects and building professionals to design and construct buildings that promote healthy circadian rhythms in occupants without a standardized indicator.

To develop such an indicator, several key factors must be considered. ***First***, a standardized boundary condition must be established to assess the window's circadian light transmission under consistent and controlled conditions. This can include standardizing window size, position, interior space and materials settings, solar and skylight spectra, and occupant positions and postures. Note that radiometric-based quantities should be standardized for all of these boundary components. ***Second***, the spectral transmittance of the window should be used as the primary input for assessing the window's ability to supply circadian light. This requires a comprehensive spectral analysis of the window's transmittance characteristics, which can be done using various spectroscopic tools and techniques or integrated into existing tools for fenestration systems such as LBNL WINDOW and OPTICS, which include the detailed spectral characteristics of the major window and glazing products in North America. ***Third***, to incorporate all the boundary components into the indicator computation, computational models must be built to simulate the circadian light conditions through the window and into the interior space as received by users. Existing modeling and simulation tools such as LARK and ALFA could be leveraged in this process.

The applications for this new indicator are wide-ranging. They could include the development of novel building codes and standards that incorporate circadian health considerations, as well as the creation of new fenestration products designed specifically to optimize circadian light transmission. Additionally, this indicator could provide building owners and occupants with valuable information regarding the potential impact of different window systems on their health and well-being. Ultimately, developing a standardized and quantitative indicator for the influence of windows on circadian health can revolutionize how buildings are designed and constructed, promoting healthy circadian rhythms and improving the overall health and well-being of occupants.

5.4. Importance of studying gaze direction relative to window position

Gaze direction illustrates the occupant's viewing direction and relative relationship to the window position, which are vital for exposure to circadian light. Like the other factors discussed in Section 4.4.1, gaze direction can affect light exposure intensity and level in cooperation with other interior parameters. Based on this review, window-ward (i.e., gaze direction perpendicular to the window) gazes obtain higher circadian light exposure as long as the room depth allows daylight penetration. However, multiple factors may affect the importance of gaze direction on the circadian light occupants receive. In particular, as described in the Results section, the circadian light conditions exposed at the spot closest to the window do not differ significantly based on the gaze direction. Similarly, the level of exposure does not significantly vary from one gaze direction to another in cloudy or overcast sky conditions in which the majority of daylight that penetrates is diffused in type. This indicates that a substantial portion of the light received by the eye comes from diffused rather than direct light when viewing from gaze directions that are not window-ward. Furthermore, variations in gaze direction along the vertical axis, a topic only discussed in Ref. [75], have been neglected in other studies; however, it was shown in that research that the variation is significant, especially when considering situations in which body posture or type of activity make the gaze direction tilt upward or downward.

It is generally accepted that exposure to natural daylight is more powerful at regulating circadian rhythms and promoting overall health than exposure to artificial or electrical light. However, the actual light intensity and spectral composition received can vary depending on the user's posture and distance from the window and the surrounding spatial and interior characteristics. The review studies found a correlation between a user's posture, distance from the window, and spatial characteristics. In addition, one factor may affect circadian light differently depending on the other two factors. For example, suppose the interiors of two identical rooms within a building have identical reflectance values, one facing north and the other south. The north-facing room requires a greater WWR. However, the same-sized WWR window could be used effectively in both rooms if an interior surface with high reflectance is used in the north-facing room compared to the south-facing room. For the purpose of creating a healthy environment that provides sufficient circadian light, it is essential to distinguish the spot of shortage and the dominance of the lighting source on the particular spot, whether it is direct or diffused light; thus, an appropriate solution could be provided based on the type of light source. For example, if diffused light is the dominant source, interior wall reflectance and WWR are two factors listed according to their effectiveness that could amplify interior circadian light. Alternatively, if direct lighting is the dominant source, south or east-facing windows and a close distance from the window could provide sufficient circadian lighting.

Studying gaze direction relative to window position has become crucial to understanding how different environmental factors can impact circadian light exposure levels, ultimately affecting sleep, mood, and overall health. This highlights the potential for future technology development in terms of human posture and view direction detection, monitoring, and prediction to better understand the relationship between windows and circadian health outcomes.

5.5. Intervention studies related to a window's impact on circadian health

The studies reviewed in this research provide important insights into the impact of windows on circadian health outcomes such as sleep quality, alertness, and well-being. While some suggested that exposure to natural light through windows can improve circadian health, others have found conflicting or mixed results. As such, much is still to be learned about the precise mechanisms and effects, especially those witnessed in controlled intervention studies. To enhance understanding of how windows impact circadian health, it is necessary to perform more rigorous control interventions and comprehensive experiments within well-controlled environments with consideration of all influential parameters and their multilateral effectiveness on circadian health. Such experiments would enable more accurate measurement of the effects of window-related factors such as glazing type, color, and position on circadian health outcomes. They would also allow for exploration of the impact of windows on other aspects of health and well-being, such as mood and cognitive function.

One area where such research could be precious is in healthcare facilities such as nursing homes, where older adults with dementia may be especially susceptible to disruptions in their circadian rhythms. By investigating the impact of windows on the sleep and overall health of these individuals, studies could identify ways to improve their quality of life.

6. Conclusion

Thirty-three sources in the study were selected to assess window performance from a circadian health perspective. Among the seven experiments focused on windows and their effects on well-being, a significant correlation was found between windows and sleep duration, sleep-related disturbances, and impairments. While most studies were simulation-based and conducted across various latitudes, appropriate window selection based on the outdoor environment and interior spatial properties that transmit high levels of circadian light and possess accountable morphological properties could provide healthy indoor environments. This review analysis accentuates the groundbreaking nature of the exploration into the use of specialized circadian light metrics, pioneering a shift away from the standard EML and CS metrics which have demonstrated a variety of outcomes. It advocates for a move beyond the limited scope of Tvis as a solitary metric, given its insufficiency in addressing the different spectral sensitivity realms of photopic and melanopic vision. Furthermore, the review brings to the fore an intricate examination of natural daylight, a universally applauded regulator of circadian rhythms and promoter of general well-being. It underscores the nuanced changes in the quality and intensity of light which are influenced by a dynamic interplay of factors including posture, proximity to light sources, and the specific spatial dynamics of a given environment. Delving deeper, the discourse unveils the pivotal relationships intertwined between physical posture, relative distance to windows, and spatial attributes, hence highlighting the urgency for a multifaceted approach in circadian lighting assessment that leverages these crucial determinants.

Despite the influence of geographical and environmental factors on solar radiation, more research, mainly controlled intervention studies, is needed to understand the potential role of window systems not only as a source of daylight for visual activities but also as medical or healthcare devices for indoor circadian health improvement. This review presents a novel perspective by addressing the divergence in outcomes with commonly used circadian light metrics like EML and CS. It underscores the need for a specialized circadian light metric while also highlighting the limitations of relying solely on Tvis due to the distinct spectral sensitivity of photopic and melanopic vision. This contribution offers a more nuanced understanding of circadian light's impact on health. Given the potential for further research on this topic, it is recommended to conduct more rigorous studies on the multilateral effectiveness of the parameters controlled over a broader range of values. It is also necessary to define a precise measurement metric with a threshold determined by the type of activity. From a practical implementation standpoint, it is necessary to establish a reliable indicator for circadian transmittance for windows. As with other thermal or optical indicators, this health-related indicator would simplify the window selection process.

In conclusion, the current preference for electric lighting for reliable circadian health underscores the importance of this technology. However, it is equally crucial to keep in sight the potential of daylighting and windows in shaping indoor circadian lighting design. The renewable qualities of daylight, along with advances in tunable LED lighting systems, as well as the development of smart glazing and window technologies that can adapt their optical characteristics in response to external triggers or user input, the integration of these elements has moved from a theoretical consideration to a practical possibility that necessitates further study. In providing evidence about specific parameters, ranges, or thresholds of window optical and morphological properties, this review lays the foundation for future investigations. By bridging the understanding between window design and indoor circadian lighting conditions, there is an aspiration to guide the development of more energy-efficient, health-promoting, and sustainable indoor environments. As it navigated the possibilities and challenges, it has been found that there is a delicate balance of human health, sustainability, and innovation.

CRediT authorship contribution statement

N. Ghaeili Ardabili: Writing – original draft, Formal analysis, Investigation, Visualization. **J. Wang:** Conceptualization, Methodology, Project administration. **N. Wang:** Initial Paper Selection and Reviews, Research Discussion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Table 5
Summary of reviewed works

REF	Objective	Research setting	Evaluation metrics	Evaluated window properties	Outcome
[60]	Development of a novel daylighting metric for human indoor circadian stimulus	Simulation (Rhinoceros, Grasshopper, Honeybee) **Type of room_** A commercial office building ($64 \times 40m^2$) Window: (Tvis -0.65) surface reflectance: **(floor:** 0.3, **wall:** 0.5, **ceiling:** 0.8) **Location:** San Francisco, CA	EML_ **Threshold:** Five days/weak with EML ≥ 250 during 7:00–10:00 a.m.	**WWR:** 30 % and 50 %, **Distance from the window:** Grid of 2 × 2, **Gaze direction:** 360° on the horizontal plane with 45-degree intervals	By increasing the WWR, all grids cover the =<50 % of stimulus frequency, and the grids with the 95 % of the stimulus frequency increase by 2.1 times. By increasing the WWR, the stimulus frequency for the points distanced from the window increases. Gazing backward provides a

(*continued on next page*)

Table 5 (*continued*)

REF	Objective	Research setting	Evaluation metrics	Evaluated window properties	Outcome
					stimulus frequency of 0/7. Gazing parallel to the window covers fewer periods of the year compared to gazing perpendicular to it.
[68]	Assessing the non-visual impact of the daylight on both mother and newborn in maternity ward	In situ measurement and Simulation (Grasshopper, Ladybug, Honeybee) **Type of room:** Double-occupancy maternity ward in Hospital (4.2 × 6.9m^2) **Window:** (Double pane, Tvis-0.8) surface reflectance: **(floor:**_0.4, **wall:** 0.7, **ceiling:** 0.7, **bed surface:**_0.6) **Location:** Harbin_ China **Cornea height:** 0.45, 0.55 & 1 *m*	EML Stimulus frequency CEA **Threshold:** Five days/weak with EML ≥ 250 during 8:00–12:00 a.m.)	**Distance from the window:** 0.7,1.5,2.9&3.7 *m* **Window orientation:** north and south	South facing window provides a minimum of 190 lx of daylight for at least 4 h a day during a sunny day. Regarding the north-facing window, the impact of the weather change on the indoor light is less sensible. During a sunny day, all considered points are exposed to 190 lx of daylight for points close to the window _within the distance of 1.5 *m* of the window_ the exposure length is at least 4 h a day. By increasing the distance, the exposure period decreases (2 h a day for a point within the 2.9 *m* of the window, and point within 3.7 *m*, it is 1 h a day). During a cloudy day, only two points of 0.45 and 0.55 at the height of 0.45 *m* and 0.55 *m* are exposed to 170 lx for 4 h a day. Regarding the stimulus frequency, for point within the 1.5 of the windows do have 90 % of ≥ 5 d/wk with the increase of distance, the percentage decrease to the 70 %
[78]	Assessing the impact of the type of glazing on the physical and emotional health of the office workers	Interventional human subject study_ Participants **Participants:** 30 office workers (63 % male and 37 % female) Age range 23–55 (average age of 34 years) **Type of room:** West facing office, **Window:** (Window with blind_ glass with Tvis 0.58 covered 75 % by a fabric roller shades with Tvis 0.015 EC window_ Tvis of 0.58 downs to 0.005) **Location:** Durham, North Carolina	CS E_v	**Tvis**	Average of CS of the case with EC glazing_ 0.42 Average of CS of the case with window and blind_ 0.05 E_v during the 7:00 to 13:00 for the case with EC glazing is in the range between 230 and 580, while, for the case with window and blind is in between 25 and 50 lx
[79]	Assessing the impact of the type of glazing on the circadian effective light in apartments	Interventional human subject study_ **Participants:** 20 residents in 16 unique apartment units (55 % Female, 40 % Male, and 5 % Non-binary Age range 21–77 (average age of 35 years) **Type of room:** 12/16 had southeast facing window and 4/16 had northwest facing window. **Window:** (EC window_ Tvis-of 0.58 downs to 0.005, Window with blind_ Tvis-0.58 and covered in half with blind) Location: Reston, Virginia, USA	CS E_v	**Tvis**	Average of CS of the case with EC glazing_ 0.156 Case with window and blind_ 0.138 Average of Melanopic lux of the case with EC glazing_ 202.4 Case with window and blind_ 177.2 In the fitted linear model, the EC glazing was evaluated as statistically significant, and the existence of EC glazing reduces the sleep onset time by 22.2 min. Besides, the EC glazing with a 0.88-point difference from the window with the blind is more effective for sleep regularity.
[61]	Evaluating the impact of the architectural feature over the circadian stimulus	Simulation_(DAYSIM)) **Type of room:** A typical hospital room (3 × 6*3m^3) **Window:** (Double pane, Tvis- 0.75) surface reflectance: **(floor:** 0.2 and 0.6, **wall:** 0.4 and 0.8, **ceiling:** 0.6 and 0.8) **Location:** London, UK. & Madrid, Spain **Cornea height:** 0.6 & 1 *m*	CS **Threshold:** CS ≥ 0.35 for at least 1 h, during 8:00 to 12:00	**WWR:** 10, 20,30,40,60 & 80 %, **Distance from the window:** _ Grid of 0.3*1m^2, 0.5 *m* distanced from side walls, **Gaze direction:** 360° on the horizontal plane with 45-degree intervals	**London & high interior surface reflectance:** value for WWR above 40 %, CS is above the threshold for both sitting and lying positions, for WWR 30 % and entire sitting positions, the value of CS was also above the threshold. By decreasing the WWR, the region with a sufficient level of CS reduces. WWR of 60 and 80 % provide the same level of CS. Low interior surface reflectance_ the window with the highest WWR

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Table 5 (*continued*)

REF	Objective	Research setting	Evaluation metrics	Evaluated window properties	Outcome
					is insufficient for providing threshold CS in lying positions in the room. However, for a sitting position for WWR above 40 %, the required threshold is met in the entire room. **Madrid & high interior surface reflectance:** WWR above 30 % is sufficient to provide the entire room with the threshold. Low interior surface reflectance_ WWR should be above 80 % to provide the CS of 0.35 in the entire room. For WWR 10 % and sitting position by a distance above 1.8 *m* from the window, the average CS was below the threshold by an increase to 20 % WWR, the area with insufficient CS starts from the distance of 3 *m* from the window, and for 30 % WWR, the limits is within the 4.2 *m* of the window. For sitting positions, WWR 10 % and 20 % were insufficient for providing the adequate level of CS for a location further than 3.3 *m* and 5.1 *m* from the windows, respectively.
[30]	Evaluating the lighting of the teaching environment from both photopic and melanopic perspective	Simulation_(DialuxEvo) **Type of room:** Four classrooms (C1:9 × 7*2.75m^3 C2:5.7 × 4.6*2.6m^3 C3:8.5 × 5.65*2.82m^3 C4:8 × 3.9*3.03m^3) surface reflectance: **(floor:** C1: 0.75, C2: 0.85, C3:0.75, C4:0.9 **wall:** C1:0.12&0.7, C2: 0.85, C3:0.82, C4:0.9 **ceiling:** C1:0.9, C2:0.85, C3:0.75, C4:0.9) **Location:** Zaragoza. Spain **Cornea Height:** 1.3 *m*	EML *m*-EDI **Threshold:** EML ≥ 250	**Distance from the window:** C1& C2:grid of 3 × 3, C3& C4: grid of 3 × 2, **Gaze direction:** Perpendicular to window, parallel to window, 45° in between the perpendicular and parallel positions **Window orientation:** C1: south_east C2: north_west C3: south_west C4: north_west	C2: approximately for all points in this room, C3: Within the 2.8 window, the EML was above the threshold and decreased beyond it. C4: Within the 2.6 window, the EML was above the threshold and decreased beyond this distance. C1: Except for point 6 (middle point close to the window), all spots have higher EML in the direction perpendicular to the window. C2, C3, C4: Directions perpendicular, 45°, and parallel to the window expose EML from high to low, respectively. C3 and C4: Worst subjectively illuminated. C1: at 11:00, the location close to the window reaches the maximum photopic E_v of 70000 lux.
[69]	Assessing the impact of the window's Tvis over photopic and melanopic lighting	In situ measurement **Type of room:** A typical room, (2.8 × 5.5m^2) **Window:** (Clear triple glazing _Tvis:0.7 Clear triple glazing with foil Orange 50 UV added_Tvis:0.39) surface reflectance: **(floor:** 0.32 **wall:** 0.74 **ceiling:** 0.74) **Cornea height:** 1.2 *m* above the ground	EML M/P ratio **Threshold:** EML ≥ 250	**Distance from the window:** 2.3& 4.1 *m* **Tvis:** 0.7 and 0.39 **Gaze direction:** perpendicular, parallel, and backward	Within the 2.3 *m* from the window, the average EML is 33.6 lux, and in no considered spot for measurement, the level of EML achieved the threshold. In the further spot, the average EML decreases to 14.3 lux. In the perpendicular direction, occupants are exposed to the maximum level of EML; when the direction gets parallel in the spot close to the window, EML gets 0.24 of the situations while facing the window. In the further spot, this ratio increases to 0.35. For the back direction, the level of EML gets minimum, and in the spot close to the window, the ratio of backward to perpendicular direction gets 0.14, while in the further spot, this ratio increased to 0.61. For Tvis 0.7, the ratio of M/P is higher than one For 0.39: the ratio of M/P gets approximately less than 0.4

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REF	Objective	Research setting	Evaluation metrics	Evaluated window properties	Outcome
[70]	Analyzing the impact of daylight on circadian rhythm	In situ measurement in the 1:5 scaled model_ **Type of room:** A typical room (actual size: 3*9m^2) **Window:** (actual size:2 × 1.5m^2 Reference room _single pane clear glass _Tvis:n/a Tested room_ UV filter_AMBER_ Tvis:0.57, TC:0.18 Antelio blue 6 mm_Tvis:0.57, Tc:0.69 Yellow color curtain_Tvis:0.24, Tc:0.08 Red color curtain_ Tvis: 0.04, Tc:0.00 Green color curtain_ Tvis: 0.21, Tc:0.09 Planibel green 6 mm_ Tvis: 0.74, Tc:0.74 Planibel Bronze 6 mm_ Tvis: 0.5, Tc:0.44 Yellow foil_ Tvis:0.86, Tc:0.56 Green foil_ Tvis: 0.57, Tc:0.43) **Location:** Bratislava in the Slovak Republic **Cornea height:** 1.2 *m* from ground	CS	**Tvis**	Ratio of the CS between the tested and reference model was reported: UV filter_AMBER_ 0.39 Antelio blue 6 mm_1 Yellow color curtain_0.11 Red color curtain_0.08 Green color curtain_0.08 Planibel green 6 mm_0.55 Planibel Bronze 6 mm_0.25 Yellow foil_0.72 Green foil_0.39
[57]	Elaborating the impact of TC coating on daylight	In situ measurement and Simulation (Rhino, Honeybee plugin, ALFA) **Type of room:** A typical furnished office room (5 × 7*3.5m^3) **Window:** (south orientated, WWR:0.57 Tio2@W-VO2 TC _Tvis:0.56 Clear Float Glass_ Tvis:0.907 Blue Tinted glass_ Tvis:0.707) surface reflectance: **(floor:** 0.35, **wall:** 0.7, **ceiling**: 0.8 **Furniture:** 0.45) **Location:** Shantou. China, Pittsburg. USA, Calgary. Canada **Cornea height:** 0.8 *m* above the ground	EML M/P Threshold: EML ≥ 250 & 550 and M/P ≥ 0.9	**Distance from the window:** 1.3 *m*, 3.5 m &5.7 *m* **Tvis** **Gaze direction:** perpendicular, parallel	1.3 *m* from window: ~2.5 % of occasions EML<250 3.5 *m* from window: ~5.5 % of occasions EML<250 5.7 *m* from window: ~7.5 % of occasions EML<250 Considering the Tvis of glazing type, the region with an M/P ratio below 0.9 are: Tio2@W-VO2 TC: 32 % M/P < 0.9 Clear Float Glass: 18 % M/P < 0.9 Blue Tinted glass: 7 % M/P < 0.9 For gazing parallel: 67 % of the room could not meet the threshold for EML.
[62]	Promoting indoor lighting of educational space for providing efficient level of circadian light	Simulation (DaySim) and validation experiment **Type of room:** A typical classroom (8 × 8*3m^3) **Window:** (located in middle of wall or above 1.5 *m* of the height_Tvis:0.75) surface reflectance: (floor:_0.2 and 0.6, wall:_0.4 and 0.8, ceiling:0.6 and 0.8) **Test cell for validation:** 2.4 × 3.2*2.7m^3 **Window:** (south facing, 1.08 × 1.16m^2, Tvis:0.75) surface reflectance: **(Wall & ceiling:** 0.72, **floor:** 0.22) **Location:** London. UK, Paris. France, and Madrid. Spain	CS CSA **Threshold:** CS ≥ 0.3	**WWR:** 30, 45 & 60 % **Window location:** Centered: center of façade, Upper: above the half height of façade. **Distance from the window:** grid of 0.4 × 1.9m^2, 0.2 *m* distanced from side walls, **Window Orientation:** north and south	Minimum of WWR according to the window orientation and simulation location: for a bright inner surface, the WWR of 30 % is sufficient for meeting the threshold in the entire class in both Madrid and Paris, for London which has mainly overcast sky, the north facing façade should have a window with 45 % WWR and 30 % WWR is sufficient for the south-facing window. In the dark inner surface, the north-facing window in London could not meet the required threshold in any WWR. For south facing window in London, both directions in Paris, and north facing window in Madrid, the WWR of 60 % is sufficient for providing the CS above 0.3. For the south facing window in Madrid, the WWR should be 45 %. With bright interior surface, a spot further from the window could be exposed to the daylight with sufficient CS. However, with the dark interior surface, the regions that meet the threshold were approximately 4.3, 4.8, and f6.2 *m* of the window for the cases with WWR of 30.45, and 60 %, respectively.

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REF	Objective	Research setting	Evaluation metrics	Evaluated window properties	Outcome
[89]	Assessing and validating the accuracy of a proposed circadian light equation.	Experiment and validation simulation (Rhinoceros, Grasshopper, Honeybee (Radiance) & EnergyPlus) _ *Experiment* **Type of room:** 1:6 scaled room (0.8 × 1*0.53m^3) surface reflectance: **inner surface:** 0.87, 0.48, 0.17 *Simulation* **Room type:** a typical classroom (5.4 × 8.6*3.3m^3) **Window:** (south facing, WWR 35 %) surface reflectance: **(floor:** 0.2 & 0.4, **ceiling and walls:** 0.4 & 0.8) **Location:** Chongqing. China	CS **Threshold:** CS ≥ 0.3 during 8:00 to 10:00	**WWR:**30, 60, and 90 %	The proposed equation: $E_{cor} = E_{cor(d)} + \left(k.\frac{\rho_{ini}}{\rho_{wall}}\right) \times WWR \times \left(\frac{\rho_{wall}}{1-\rho}\right)$ According to the simulation output, the interior surface reflectance is more effective than WWR, as S2 met the CS threshold in the entire room and was more energy efficient.
[63]	Assessing and validating the accuracy of a proposed circadian light equation.	Simulation (Rhinoceros, Grasshopper, Honeybee & ladybug (Radiance)) **Type of room:** (4.8 × 3*3.2m^3) surface reflectance **(interior surface):** 0.5,0.6,0.7,0.8, 0.9 **Location:** Helsinki, Finland. **Cornea height:** 1.2 *m* above the floor	Corneal illuminance	**WWR:**0–100 %	The proposed equation: $E_{cor,avg(i)} = C_2.WWR.\frac{\rho}{1-\rho}$ The surface reflectance of a room has a substantial impact on corneal illuminance. Inter-reflected light can significantly contribute to corneal illuminance with high surface reflectance. Helsinki = For rooms with the reflectance of 0.4 and WWR, 90 % entire room achieves 230lx corneal illuminance, For rooms with reflectance 0.8, regardless of WWR entire room achieve corneal illuminance above 200.
[80]	Assessments of the colored glazing impact on alertness and well-being	Interventional human subject study **Participants:** 17 students (Age_ 22.68 ±1.8 years) **Type of room:** A typical office room (3.8 × 6.2*3.2m^3) **Window:** (south-facing, 2.3 × 2.3m^2) surface reflectance: **(floor:**0.3, **wall:**0.88, **ceiling:**0.88) **Location:** Beijing. China	CS	**Tvis:** 0.91(clear), 0.55(blue), 0.37 (bronze), 0.68 (green) & 0.22 (grey)	CS was calculated in the spot approximately 1.8 *m* distance from the window. 0.91 (clear): 0.357 0.55 (blue):0.417 0.37 (bronze): 0.333 0.68 (green): 0.487 0.22 (grey): 0.464 Self-report: there is a statistically significant correlation between glazing color and well-being [F = 3.619, p-value = 0.006] Correlation between CS and reply to non-visual questions: There is significant correlation between Relaxing and CS [F = 0.617, p-value = 0.017], and alertness [F = 0.255, p-value = 0.05]
[71]	Evaluation the circadian effectiveness of daylit space	In situ measurement **Type of room:** 9 daylit units at dementia care facilities and compared to 4 non-daylit units. **Location:** Southern California. USA	EML M/P **Threshold:** EML ≥ 250	**Distance from the window:** 1, 3, and 5 *m* from window **Gaze direction:** 360° on the horizontal plane with 90-degree intervals	Distance from window: [EML, M/P] 1 *m*: Gazing direction_ Perpendicular_ [732 lux, 0.97] Parallel_ [141 lux, 0.73] Away_ [59 lux, 0.52] 3 *m*: Gazing direction_ Perpendicular_ [243 lux, 0.81] Parallel_ [94 lux, 0.59] Away_ [56 lux, 0.49] 5 *m*: Perpendicular_ [132 lux, 0.69] Parallel_ [66 lux, 0.53] Away_ [42 lux, 0.49]
[81]	Assessments of the colored glazing impact on alertness and well-being	Interventional human subject study **Participants:** (11 students (6 males and 5 females.) Age_ 22.27 ±2.95 years)) **Type of room:** A typical office room (3.8 × 6.2*3.2m^3) **Window:** (south-facing, 2.3 × 2.3m^2) surface reflectance: **(floor:**	CS **Threshold:** CS ≥ 0.3	**Tvis:** 0.91(clear), 0.55(blue), 0.38 (bronze), 0.75(grey) 0.22 (green), 0.54 (dark blue) & 0.35 (Red)	CS calculated the spot within the approximately 1.8 *m* distance from the window.: Clear, blue, and green glazing provides the demanded CS level for the entire experiment duration. For red, grey, and yellow glazing, the CS value is below the threshold before 9:15, 9:40, and

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REF	Objective	Research setting	Evaluation metrics	Evaluated window properties	Outcome
		0.3, **wall:** 0.88,**ceiling:** 0.88) **Location:** Beijing. China			9:50 in the morning. Dark blue glazing does not provide the required CS level entire day. **Self-report:** there is no significant correlation between glazing color and alertness [F = 1.955, p-value = 0.07]
[64]	Evaluation of electric light and daylight performance simultaneously from circadian efficiency for regulation of luminous flux of electric lighting according to daylight	Simulation (Daylight Visualizer) **Type of room:** (A 24/7 hospital laboratory 13 × 15*2.7 m^3) **Window:** (north and south facing, Tvis: 0.78) surface reflectance: **(floor:** 0.2) **Location:** Seville, Spain. **Cornea height:** 1.55 *m* from ground	CS **Threshold:** CS ≥ 0.3	**WWR:** 20 %, 30 %,40 % **Distance from the window:** grid of 1(perpendicular to window) *2 (parallel to window) m^2 **Orientation:** north and south	WWR_20 %: The north-facing window threshold met within the 1.1 *m* window during the summer. For the south-facing window, the distance increases roughly to 1.4 *m*. WWR_30 % North facing window area within the 2.5 and 3.8 *m* of the window provides demanded CS during the winter and summer, respectively. South facing window area within the 3 and 3.8 *m* of the window provides demanded CS during the winter and summer respectively. WWR_40 % North facing window area within the 2.8 and 4.1 *m* of the window provides demanded CS during the winter and summer, respectively. South facing window area within the 4.3 and 5 *m* of the window provides demanded CS during the winter and summer, respectively.
[72]	Evaluation of the impact of combination of different glazing types with interior wall call were evaluated	In situ measurement with simulation (ALFA) **Type of room:** A typical office (3 × 4*2.6 m^3) **Window:** north orientated (1.4 × 0.9m^2, WWR:16 %), surface reflectance: **(wall:** ~0.75, ~0.5, ~0.27 **Default**: 0.87, 0.61) **Location:** Ljubljana, Slovenia **Cornea height:** 1.2 *m* above the ground	CS EML RME Threshold: CS ≥ 0.3, EML ≥ 200	**Tvis_** 0.8 (double clear panes), 0.76 (Two clear glass panes, inner with low-e coating), 0.46 (Three clear glass panes, inner and outer with low-e coating.), 0.44 (Bronze tinted outer and clear inner glass pane), 0.39 (Blue tinted outer and clear inner glass pane), 0.25 (Dark blue tinted outer and clear inner glass pane), 0.46 (Outer pane with solar protective spectrally selective coating and clear inner glass pane)	*Experiment:* In general Dark blue tinted outer and clear inner glass pane provides higher RME, a combination of this window with a dark blue wall gives the highest ratio of RME = ~1.85 The worst window is double pane glazing with one clear and one Bronze tinted glass pane, and the combination of this glazing with dark red wall provides the lowest RME = ~0.6 The high value of RME is due to the low level of photopic illuminance, which for all scenarios was below 875 lx. *Simulation:* The best scenario that met the CS threshold is a combination of double pane glazing with one clear and one low-e coated glass pane with Blue with 0.595 reflectance. The worst combination, which only provides CS > 0.3 from 9:00 to 15:00, is Bronze tinted outer and clear inner glass pane with an orange wall with 0.564 reflectance. For EML metrics, the same combinations of wall and glazing presented a high and low level of EML; the difference is the duration of efficiency. For the worst combination in EML metric, the period is between 9:00 to 16:00
[73]	Assessment of indoor lighting (electric and daylight) of dementia unit to determination of illumination level provided by electric light	In situ measurement_ **Type of room:** Living room in dementia unit of 15 dementia units (m^3) **Location:** Norwegian **Cornea height:** 1.2 *m* above the floor	*m*-EDI **Threshold:** *m*-EDI ≥ 217 lx	**Gaze direction:** 360° on the horizontal plane with 90-degree intervals	The median of *m*-EDI for summer is 186, while it decreased to 98 during the winter. According to the fitted model, as a correlation between the gazing direction during the summer and winter, the gazing direction is statistically significant, and in case the gazing direction is toward to window increases the *m*-EDI level

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REF	Objective	Research setting	Evaluation metrics	Evaluated window properties	Outcome
					by 0.85 times in comparison to inward gazing direction. However, during the winter gazing direction is not significant [F = 0.62, p-value = 0.106] Inward gazing: 2/15 of dementia units met the threshold during summer and none during the winter. Window- ward gazing: 6/15 during summer and 1/15 during winter
[74]	Evaluating the daylighting levels in apartments of Melbourne to distinguish the impact of legislations on indoor daylighting.	In situ measurement & simulation (Revit) **Type of room:** bedrooms in dementia unit of 12 apartments (area arrange 6~9m^2) **Window:** (WFR:30–100 % one bedroom had borrowed window WFR 44 % and for two bedrooms 0 %) **Location:** Melbourne, Australia. **Cornea height:** 0.8 *m* from ground	EML **Threshold:** EML ≥ 250	**Orientation:** north, west, east, north-east, north-west, south-east, and south-west **Distance from window:** no actual size, two spots, one close to window and the other one is the farthest corner from window, considered for measurement. **Estimated range for distant point is (3.6–4.2 *m*)	For all cases, the threshold is met by the spots close to the window except for the case with a borrowed window. Spots that met the thresholds were: Two west-oriented windows_ with WFR of 37.5 % and 33 % and two southwest-oriented windows with WFR of 62.5 % and 100 %
[75]	Assessment of the electric and daylight on the circadian health	In situ measurement Type of room: classroom in a university **Window:** (west-oriented, Tvis: 0.68) surface reflectance: **(floor:** 0.75, **wall:** 0.89, **ceiling:** 0.94) **Location:** Naples, Italy.	Melatonin suppression index	**Gaze direction in vertical plane:** 0° facing board, 15° tilted head toward desk, and 45 ° tilted head toward desk. **Distance from window_** no exact data about the distance, according to shared layout plan, three seats (A, B,C) are approximately in the same line within the distance approximately ~2 *m* seat A facing the wall in its outward gazing direction, seat B facing edge of window while gazing outward, and seat C completely facing window with outward gazing. Seat D has closer distance to window approximately (~1.5 *m* from window) and its gazing direction is like seat B.	Melatonin suppression ranges between 0 and 57 %. Seat D has an overall higher percentage of melatonin suppression. Among three seats A, B, and C, seat A has the highest rate relative to the other two seats under the clear sky, Under an overcast sky, the range is between 1 and 53 %. Again, seat D has a better condition in comparison to other seats. By tilting the head toward the desk, the percentage of suppression decreases.
[65]	Developing a circadian lighting guideline for home design	Simulation (DAYSIM) **Type of room:** an average unit modeled identical to 20 units measured and surveyed (3.7 × 6.2*3 m^3) **Window:** (south and north orientated, 0.8 × 1.4 m^2) surface reflectance: **(wall:** 0.2–0.8) **Location:** Boston, USA.	DA **Threshold:** 190 lux	**Gaze direction:** 360° on the horizontal plane with 45-degree intervals **Distance from window:** 1.8–5.4 *m* **Window orientation:** south and north orientated.	Gazing direction_ highest value was for direction toward window by ~66 %, the second and third highest values are for direction toward right and left respectively. Lowest is toward left-away by 20 % Distance from window_ Distance from window is more effective when the occupant facing toward the window, in the case occupant facing away the window, more than distance, interior wall reflectance is effective in the level DA. For south facing windows, by increasing the interior surface reflectance from 0.2 to 0.8, daylight autonomy increases from 26.4 % to 41.5 % For north facing windows, by increases of interior surface reflectance to 0.8, daylight autonomy raises from 22.5 % to 72.5 %
[86]	Developing a circadian metric of daylight for virtual observer	In situ measurement (CLLS) and simulation (DAYSIM) **Type of room:** (test room (~4.5 × 3.04 m^2) with two camera, C1 within the 1.37 *m* of window facing parallel the window, second camera C2 within the 4.17 of window and facing toward the window.) **Window:** (south facing, double glazed insulated,	Circadian weighted irradiance (E_{ec}) (W/m^2)	**Distance from window:** 1,2,3& 4 *m* from window **Gaze direction:** parallel and perpendicular to window **Different shading system:** (Venetian blinds) and OLS (Optical louver system)	**VB:** for the case facing parallel to window direction, within the close distance to window higher E_{ec} measured it gets a peak at 13:00, which is approximately 0.4 The case facing perpendicular to the window spot within the 2 and 3 *m* of the window captured the same E_{ec} after 13:00 when spot 3 achieved the highest level of ~0.7.

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REF	Objective	Research setting	Evaluation metrics	Evaluated window properties	Outcome
		Tvis: 0.62 with two type of different shading systems for windows) surface reflectance: **(floor:** 0.23, **wall:** 0.65, **ceiling:** 0.82) **Location:** Berkeley, USA. **Cornea height:** 1.2 *m* above ground			**OLS:** for the case facing parallel to the window, location 1 *m* to the window achieved the highest level of E_{ec} at 11:00 (~0.44 W\m2), while for the case with the direction of facing perpendicular to the window, spot within 4 *m* of window receives the highest level of E_{ec} ~0.44.
[56]	Comparison of the two EML and CS metrics accuracy for the assessment of the indoor circadian light	In situ measurement and simulation (_) **Type of room:** three open plan office with one private office room (*N*-north faced:8 × 6.4, *S*-south faced:8.8 × 5.6, E− east faced:11.5 × 6.4, and W- west faced:6.4 × 3.2 m^2). **Window:** (N:55 %, S:70 %, E:62 % & W:80 %) surface reflectance: **(floor:** 0.4, **wall:** 0.9, **ceiling:** 0.78) **Location:** Chongqing, China. Cornea height: 1.2 *m* above the ground	EML CS **Threshold:** CS ≥ 0.3, EML ≥ 240	**Window orientation:** north, east, west, and south **Distance from window:** open plan office, 1.5 and 4.5 *m* from window **Gaze direction:** two parallel directions with window and back ward direction	Gazing direction for: N: maximum CS measured for gazing parallel the window direction to the west. E: maximum CS measured for gazing parallel the window direction to the South. S: maximum CS measured for gazing parallel to the window direction to the east. W: maximum CS measured for gazing parallel to the window direction to the north. South and west-facing windows provide CS above 0.3. With the EML metric, only office S met the threshold of 240 lx between 10:30 to 13:30. Distance from window_ in none of the directions, the distance of 4.5 *m* from the window does not provide CS above 0.3.
[88]	Developing in-depth understanding of the indoor circadian lighting by adopting the new measurement techniques	In situ measurement and simulation (Rhino, Grasshopper, Honeybee and Lark) **Type of room:** Activity room in dementia care (7 × 11m^2). **Window:** (South facing, WWR:25 %) **Location:** Los Angeles, USA.	Circadian Frequency (CF) Threshold EML ≥ 250	**Gaze direction:** 360° on the horizontal plane with 45-degree intervals **Distance from window:** a grid of 7 × 11 **Adding skylight:** (Ratio: 0.1, 0.2, 0.3, 0.4)	Within the 2 *m* of the window, there is the spot with specifically window-ward gazing direction which has circadian frequency over 80 %; this is while for spots just next to the window where circadian frequency for backward gazing direction is 0. For areas further than 2 *m* from the window, circadian frequency values range between 40 and 0. The total circadian frequency average for the entire room is 18 %, and the area with EML above 250 is 5 % of the room. Skylight enhances indoor circadian light by 0.1 ratio of the skylight, the circadian frequency average increases 1.8 times, and by increasing the ratio by 0.1 step intervals, the average circadian frequency increases 1.11 times. From the area with EML over 250, the big changes occur when the ratio changes from 0.2 to 0.3, increasing acceptable areas from 8 % to 32 %.
[85]	Evaluating the impact of the seasonal change of daylight on circadian light	In situ measurement and **Type of room:** three offices in University (OF1: 3.89 × 3.79$m^{2,}$ OF2: 3.36 × 4.35m^2, OF3: 3.48 × 2.79 + 3.44 × 1.78m^2). Window_ clear glass, WWR: (OF1: 45 %, OF2:40 %, OF3:20 %) **Location:** Naples, Italy.	CS	**Window orientation:** OF1: west OF2: east OF3: south	OF1: During summer and winter, CS was above the threshold under the clear sky and had the same trend of variation with roughly the same values, except after 15:00. During the variable sky day, again, entire days CS values were above the threshold. OF2: During summer and winter and under the clear and variable sky, CS is above the threshold, and there is roughly at least a 0.05 difference between CS during summer and winter. OF3: During summer and winter and under both sky conditions, CS was above the threshold.

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Table 5 (*continued*)

REF	Objective	Research setting	Evaluation metrics	Evaluated window properties	Outcome
[82]	Evaluating the impact of the EC glazing on the sleep quality and productivity	Interventional human subject study **Participants:** (30 participants (36.66 % Female and 63.33 % Male Age range 21–65 (average: 34 years)) **Type of room:** West facing room **Window: (**window with blind: glass with Tvis 0.58 covered 75 % by a fabric roller shades with 0.015 Tvis EC window: Tvis of 0.58 downs to 0.005)	CS EML	**Tvis** **Gaze direction:** perpendicular and parallel to window	Average of CS: Case with EC glazing_ 0.42 Case with window and blind_ 0.05 Average of EML of the case_ facing north EC glazing_ 143 Window and blind_ 18.3 facing south EC glazing_ 151 Window and blind_ 20.7 facing west EC glazing_ 316 Window and blind_ 40.6 In the fitted linear model, the EC glazing was evaluated as statistically significant on sleep duration. Participants in the office with EC had an increase of 19.7min in sleep duration, while in the room with blind, the sleep duration decreased by 14min from the baseline.
[66]	Developing approach for simulating and analyzing photopic and circadian illuminance of daylight	Simulation (ALFA) **Type of room:** (an office 12.2 × 21.3*3.1m^2). **Window:** (south facing, WWR:40 % Tvis: 0.7) surface reflectance: **(floor:** 0.38, **wall:** 0.81, **ceiling:** 0.82) **Location:** Seattle, USA. Cornea height: 1.2 *m* above the ground	EML **Threshold:** EML ≥ 240	**Gaze direction:** 360° on the horizontal plane with 45-degree intervals **Distance from window:** grid 0.6 × 0.6 m^2 with 1 *m* offset from walls. **Window's head height with fixed WWR_** 2.1 *m* and 2.7 *m* **Window orientation:** north, east, west, south. **Shading system:** overhang with 1.4 *m* depth, horizontal blinds 10 cm depth and 3.75 space, EC with Tvis 0.18 and 0.06	The depth of the region that meets the threshold for gaze direction toward the window, parallel to the window, and away from the window was 21 *m*, 12 *m*, and 7 *m*, respectively. Window's head height with fixed WWR: penetration depth increased by 2.6 *m*, 1.5 *m*, and 0.9 *m* per 0.3 *m* of additional head height for gazing toward, parallel to, and away from the window. The effect of this parameter is distinguished as insignificant in comparison to other factors. Changing orientation toward the north decreases the penetration depth of circadian light by 14.6 *m*. The variance between north, east, and west orientation is 1.8 *m*. Shading system: Overhang: reduced penetration depth by 1.5 *m* Horizontal blinds: reduced penetration depth by 0.3 *m* EC_0.18: reduction of penetration depth to 7.6 *m*. EC_0.06: reduction of penetration depth to 3.3 *m*
[87]	Assessment of the PDLC window performance from visual, thermal, and circadian perspective	In situ measurement **Type of room:** (A test cell, 4 × 4*2.3m^3). Window_ PDLC, west oriented, WWR: (1.3 × 1.3m^3) **Location:** MIT-Manipal, India. Cornea height: 1.2 *m* above the ground	CS **Threshold:** CS ≥ 0.3, for 2 h during the daytime	**Tvis**	The maximum variation of CS between the opaque and clear states of the glass was 0.1. During the experiment duration, the CS level was above the threshold. During the early times of the day, CS was 0.4, reaching 0.6 at 16:00; this increment is due to the window orientation.
[67]	Analyzing the impact of the daylight variation of the circadian light	Simulation (ALFA) **Type of room:** (An office 4.3 × 6.2*2.6m^3). **Window:** (Two glass with 1.2 × 0.76 m^2 Tvis: 0.78) surface reflectance: **(floor:** 0.38, **wall:** 0.8, **ceiling:** 0.82) **Location:** Copenhagen, Denmark. **Cornea height:** 1.2 *m*	*m*-EDI **Threshold:** *m*-EDI ≥ 250, for 2 h during the daytime	**Window orientation:** south, west, east, north	During the autumn, spring, and winter, the threshold was met in all directions, but during the winter, only during noon and under the clear sky, the *m*-EDI was above the threshold for all four directions, at 15:00 under the clear sky, the *m*-EDI for case window west oriented, is above the threshold
[84]	Analyzing various case of lighting and corresponding impact on circadian light.	In situ measurement and simulation (DIALUX EVO) **Type of room:** (an open plan office for simulation. A test room for experiment (4 × 4*2.3m^3)) Window_ clear north and west	CS **Threshold:** CS ≥ 250, for 2 h during the daytime	**Shading system** **Gaze direction:** 360° on the horizontal plane with 45-degree intervals **Distance from window:** venetian blinds	Attachment of the shading system does not impact the level of CS, and in all cases at different seasonal conditions, the CS was above 0.3 during the day hours. The occupant gazing window ward had a high E_v

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Table 5 (*continued*)

REF	Objective	Research setting	Evaluation metrics	Evaluated window properties	Outcome
		facing glass, (1.3 × 1.3 m^2) with and without blind Tvis: **Location:** Manipal, India. **Cornea height:** 1.2 *m*			level; the lowest was for the backward gazing direction. Occupants by a distance of 3.3 from the north window and 5.5 from the west have the minimum level of CS. By increasing the distance from 1.2 to 3.7 *m*, the CS level decreases roughly 0.11 before 16:30. Close to sunset, the variance reduces.
[76]	Assessment the correlation EML and subjective responses to questionnaire regarding circadian light	Interventional human subject study and simulation (ALFA for Rhino) **Participants:** 542 participants (60 % Female and 40 % Male Age average: 22.2 years **Type of room:** (C1: 19 × 8.5m^2, with window NE oriented and WWR:70 % C2: 14.3 × 11.2m^2, with window SE oriented and WWR:100 % C3:8.9 × 19.7m^2, with window SE & NW oriented and WWR:17 % C4:6.7 × 14.9m^2, with window W oriented and WWR:28 % C5:5.7 × 12.4m^2, with window E oriented and WWR:26 % C6:6.5 × 17.8m^2, with window N oriented and WWR:22 % C7:14.1 × 21.3m^2, with window NW & NE oriented and WWR:72 % C8:6.6 × 34.1m^2, with window N & S oriented and WWR:6 %) **Survey:** DAYKE-Europe survey **Cornea height:** 1.2 *m* above ground	EML **Threshold:** EML ≥ 250	**WWR_** **Orientation_**	Simulation: C1, C2, C5, C6, C7, and C8 met the required threshold for EML during the spring season under both overcast and sunny skies. However, during the winter, only C1 does meet the requirement. The correlation between simulated EML and energy saving: there is a statistically significant correlation between EML and energy saving [F = −0.483, p-value<0.001] Survey: The correlation between survey response and simulated EML: ~daylight quantity [F = 0.33, p-value<0.001] ~visual performance [F = 0.257, p-value<0.001] ~daylight quality [F = 0.4, p-value<0.001] ~window quality [F = 0.162, p-value<0.001] ~view out quality [F = 0.323, p-value<0.001]
[83]	Developing an optimal lighting assessment with consideration of both visual and non-visual aspect of light from energy conception perspective	In situ measurement and simulation (DAYSIM) **Type of room:** A typical office for simulation. A test room for experiment (3.36 × 5.5*2.4m^3) Window: (clear north and west facing glass, (1.3 × 1.3 m^2) with and without blind Tvis: 0.615) surface reflectance: **(floor:** 0.285, **wall:** 0.36–0.56, **ceiling:** 0.892) **Location:** Beijing & Chongqing, China.	EML **Threshold:** EML ≥ 250 and 300lx illuminance	**WWR:**38.6 % 56 % **Orientation:** north & east **Distance from window:** 1.5, 2.5, &3.5 *m* away from window	Annual lighting energy consumption variation for providing 300 lx of visual light with 250 EM L non-visual light in comparison to the case with 300 lx baseline: Chongqing_WWR-38.6 %: North = 39 % East: 26 % Beijing_WWR-38.6 %: North = 16 % East: 10 % Chongqing_WWR-56 %: North = 30 % East: 19 % Beijing_WWR-56 %: North = 6 % East: 5 %
[77]	Recognition of the indoor daylighting responsible for occupants' both visual and thermal satisfaction	Interventional human subject study & simulation (DIVA) **Participants:** 16 men average age: 24.9 years **Type of room:** two identical and adjacent Climate chamber (24m^2) **Window:** (triple-paned window, WWR = 70 %) **Location:** Karlsruhe, Germany **Cornea height:** 0.9 *m* above ground	a_{cv} E_v	**Orientation:** equatorial and non-equatorial	Correlation between a_{cv} and response: There is no correlation at the first stamp; however, during the second stamp, a significant correlation [F = −0.554, p-value = 0.05] in non-equatorial façade between the a_{cv} and preference with illumination and [F = −0.531, p-value = 0.05] in equatorial façade between the satisfaction with room illumination and a_{cv} found During the third stamp, for summer, in non-equatorial façade orientation, a significant correlation [F = −0.715, p-value = 0.01] between a_{cv} and preference with illumination was found

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