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Review

Role of Architectural Design in Creating Circadian-Effective Interior Settings

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Abstract: Daylight variability throughout the day makes it an ideal light source for the stimulation of humans' circadian systems. However, the key criteria, including proper quantity, quality, and hours of access to daylight, are not always present inside the built environment. Therefore, artificial light is necessary to complement the human's visual and non-visual needs for light. Architectural design parameters, such as window area, orientation, glazing material, and surface reflectance alter the characteristics of both daylight and artificial light inside buildings. These parameters and their impact on lighting design should be considered from the early design stages to attain a circadian-effective design. In response to this need, a design approach called Human-Centric Lighting (HCL) was introduced. HCL places humans, and their visual and non-visual needs, in the center of the design process. It manipulates the light-related factors, such as spectrum and intensity, within the built environment for circadian benefits. The effect of HCL on lighting energy efficiency is still not clear. This paper reviews essential architectural design parameters and their impacts on circadian lighting design, considers the HCL design process and explores the most widely used circadian lighting metrics and standards.

Keywords: circadian-effective lighting; architectural design parameters; human-centric lighting; standards and recommendations

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1. Introduction

Although daylight and artificial light can satisfy humans' visual and non-visual needs, daylight is usually preferred [1,2]. For decades, the main reason for the increasing use of daylighting was to reduce energy use, but recent studies started to also look into the non-visual benefits of daylight, and how to balance the non-visual lighting requirements with visual comfort and energy consumption [3]. A study reported that populations living in remote areas, under just daylight, have better sleep quantity and quality than those using electrical light [4]. Another study found that living in windowless environments with no/low access to daylight results in circadian disruption and poorer sleep quality and quantity [5]. However, very few short-time studies looked into the entraining effects of daylight under real-life conditions [6,7]. This may go back to the difficulty of controlling daylight compared to electric lighting, where advanced technology is used to design and engineer the desired lighting quality and quantity [6].

Daylight varies in intensity, spectral power distribution (SPD), and direction throughout the days and seasons [8]. This variability makes daylight an ideal light source for circadian system activation, as it provides the proper spectrum and intensity of light at the right times (i.e., during the day) [9–13]. Modern people working indoors are exposed to fixed artificial lighting conditions for long times. This meets their visual needs, but does not necessarily provide the proper light intensity and spectral composition required for the stimulation of the circadian system, thus leading to circadian disruption [14–16]. Studies tried to lessen the problem by simulating natural light's wavelengths and color temperatures using light-emitting diode (LED) fixtures [14,17–21]. The challenge was to fully match the continuous visible spectrum of the natural light by mixing the LEDs [20]. In addition, daylight intensity is about 10–50 times more than the indoor lights used in built environments, with a spectrum that is very different from electric light sources and shows different patterns [22]. Daylight imitation is never fully achieved due to budget limitations and energy codes [9,23]. However, the results of previous studies showed that daylight-like lights have beneficial effects on sleep, alertness, mood, and visual comfort [20,24].

The dynamics of daylight result in different outcomes depending on the location, urban context, and weather conditions [6,8]. Daylight SPD and correlated color temperature (CCT) change throughout the day depending on the cloud cover [8]. Daylight CCT ranges between 4000 K on cloudy days and 40,000 K on clear days, while wavelengths that make up daylight cover the entire visible spectrum (i.e., 380–780 nm) [8,25]. Morning light (6:00–9:00 a.m.) has more light in the blue region, while late afternoon light (after 4:00 p.m.) has more in the orange–red region of the daylight spectrum. These natural changes balance the human circadian rhythms [21,26]. For example, exposure to morning light that is rich with short wavelengths entrains the circadian rhythms.

Daylight includes light coming from the sun disc (i.e., direct solar radiation) and light coming from the sky (i.e., diffuse solar radiation). The term "daylighting" describes the process by which daylight is employed to illuminate the indoor spaces through openings in the building's exterior [6]. Studies on the non-visual effects of daylight are gaining more attention, especially in spaces where performance, mood, and alertness are very important, such as classrooms and offices [27]. Daylighting at workspaces and classrooms is known as a critical factor that can significantly affect the productivity of workers and students, as well as their overall satisfaction and wellbeing [9,28–31]. Consequently, designing for both the visual and circadian potentials of daylight should be considered in lighting design [32].

Besides the visual and non-visual benefits, daylight use in the built environment is important to decrease the energy consumption caused by electric lighting [33]. When daylight is not present or sufficient, electric lighting systems are used to satisfy lighting requirements [33,34]. The energy efficiency of these artificial systems is significantly determined by occupants' behaviors. Traditional lighting systems consist of lighting fixtures and switches, and they are manually controlled by occupants who tend to forget to turn off the lights after leaving the space [35]. Hence, lighting control systems are necessary to reduce a building's energy consumption [36].

Sensor-based lighting has been used for a very long time as a central control system. The sensors detect occupancy, motion, or other external factors and adjust lighting levels based on these factors [33,34]. Daylight sensors are placed in spaces where natural light can satisfy full or partial lighting requirements. Sensors' primary function is to detect daylight, while daylight-linked control systems switch or dim electric light when daylight is present [37]. Previous studies reported high energy savings resulting from daylight-linked control systems, which can be over 40% [38]. Energy savings can be even more if daylight sensors are combined with motion sensors [39]. In addition to reducing energy consumption, sensor-based lighting systems can adjust the lighting intensity and color temperature to match the user's preference, and thus, can positively affect the user's circadian rhythm and increase productivity [34].

A lighting control system is considered a smart lighting system (SLS) if it uses advanced building technology and an internet-based network to convey data [33]. LEDs are the most efficient artificial light sources today, and they form the foundation of many emerging technologies and current lighting systems, including SLSs [33,34]. LEDs have the ability to change light intensity and color temperature, but they need to be combined with control systems and sensors to form SLSs. The technical systems of SLSs (LEDs, sensors, and control systems) can be designed to influence the visual and non-visual effects of light on humans. Füchtenhans et al. (2021) reported that light sensors and controls are the most investigated technical aspects of SLSs, and the objective is mainly to reduce energy consumption and improve sustainability in residential spaces, offices, and outdoor environments [34]. More research is needed to propose methods for the design of SLSs to support humans' physiological and psychological health [40].

This paper aims to investigate the role of architectural design in modifying the characteristics of light inside the built environment and the ways in which these characteristics impact the circadian effectiveness of the interior settings. It aims to provide general guideline on the best practices of architectural design to support humans' non-visual light needs. This paper is structured as follows: Section 2 outlines the methodology followed to generate the literature review, Section 3 describes the basic interaction between the architectural design and daylight, Section 4 discusses the architectural design parameters reported by current research with regard to non-visual light effects, Section 5 identifies the role of human-centric design and artificial lighting in supporting circadian stimulation, Section 6 reviews the current circadian lighting design standards and recommendations, Section 7 discusses the findings of this review, and Section 8 provides conclusions, recommendations, and proposes issues for future work.

2. Methodology

The interaction of architecture and light, whether natural light or artificial light, influences the visual and non-visual light effects inside the built environment. This study builds on the review conducted by Bellia and Fragliasso (2021), which classified the architectural factors affecting the non-visual effects of light based on the design scale. The classification included urban, architectural, technological, and interior design [41]. While Bellia and Fragliasso (2021) focused more on the role of architecture in shaping the characteristics of daylight after it enters the built environment, this study is more comprehensive and it reviews the effect of architectural design on indoor lighting characteristics affecting the circadian system, irrespective of whether the light source is natural or artificial. Studies investigating the influence of architecture on the non-visual effects of light are categorized based on the architectural design factor they investigate. These factors are windows' characteristics, shading devices and external obstruction, and surfaces' color and reflectance, space depth, and glazing properties.

The articles, reports, and standards used in this review were identified across two databases: Scopus and Web of Science, for the period between 2010 and 2021. The research was limited to 'Engineering' papers in Scopus, and to 'Construction Building Technology' and 'Public Environmental Occupational Health' papers in Web of Science. The following keywords were used in both search engines: non-visual effects of light, circadian lighting design, human centric lighting, circadian lighting standards and recommendations, circadian stimulus, and equivalent melanopic lux. Table 1 shows the results for the keywords in each database.

Table 1. Keywords used in the literature search.

Keyword	Scopus	Web of Science
Non-visual effects of light	107	40
Circadian lighting design	88	107
Human centric lighting	121	30
Circadian lighting standards and recommendations	2	1
Circadian stimulus	81	45
Equivalent melanopic lux	10	6
Total	409	229

Only studies related to the architectural design factors and artificial lighting features were selected for further analysis. Eligibility was assessed by reading abstracts, and the whole research paper when necessary. Papers were then classified based on the architectural parameters they investigated. The following data were extracted from the papers (if available): the light source (natural light, artificial light, or a combination), the investigated architectural parameters, light-related factors (spectrum, intensity, spatial pattern, or temporal pattern), and the resulting circadian potential. The following figure (Figure 1) explains the general framework of the literature review conducted.

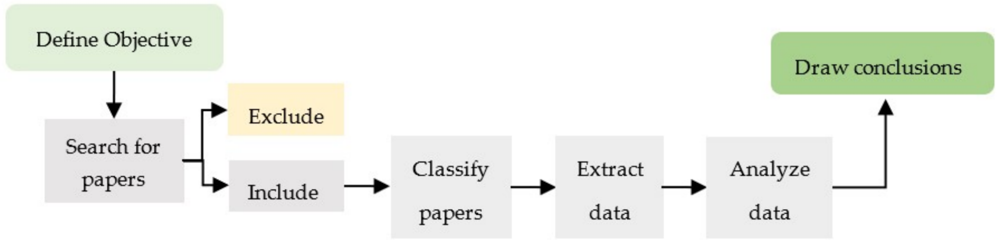

Figure 1. Workflow of the research methodology.

3. Architectural Design and Daylighting Interaction

Architectural styles throughout the world have developed over centuries in response to local imperatives (e.g., cultural, weather conditions, etc.), with the help of evolving building technologies and construction methods. However, the use of daylighting design that is relevant to each climate or location continued as a rule-of-thumb for a long period. The availability of glass for windows upgraded the role of building apertures from protection against extreme weather conditions to providing daylight [42]. Architectural design and daylighting affect each other. The limitations of daylight as a source affect architecture such as floor depth, building form, and other design parameters [15]. On the other hand, design guidelines and building regulations influence daylighting design, such as the regulations on buildings' heights, and how they affect daylight's access to architectural spaces and shadow the surrounding buildings [30].

Architectural lighting, both artificial and daylight, has traditionally been designed to fulfill only visual performance and comfort requirements [43]. Recently, it became clear that architecture and architectural lighting also have a role in affecting the non-visual comfort aspects of buildings' occupants [41,43]. Factors affecting the circadian rhythms, such as the intensity and spectrum of light, are significantly determined by the built environment [44]. Understanding how light and architecture interact is crucial to design spaces that are both visually and non-visually comfortable [41,45]. New findings in light non-visual studies should be used to update lighting strategies, which might also affect architectural design practices. Hraska (2015) suggested that an integrated approach, which addresses the interaction between lighting sources (both daylight and artificial), interior design, building design, and site planning should be followed to design environments that satisfy visual and non-visual lighting requirements [26].

Vas and Inanici (2020) performed lighting simulations to evaluate the effect of architectural parameters on the visual and non-visual potency of daylight within spaces [45]. Non-visual potency refers to the efficiency of a light stimulus in terms of influencing human biological responses [29]. Simulations indicated that daylight could be an important source for sufficient circadian lighting, but only if effective architectural parameters are identified and effectively integrated into designs from the early stages. Vas and Inanici (2020) introduced three guidelines for designers and architects to design spaces requiring effective circadian lighting. The first guideline suggests studying the project context and identifying potential obstructions that may inhibit daylight access. The second recommends avoiding the usage of shading strategies that obstruct views to the sky. The study stated that shading devices that reduce glare without obstructing the view, such as horizontal blinds, had minimal to no impact on circadian lighting. The final guideline advises orienting the seating areas, located over 20 ft from a window, to face the nearest window, thus maximizing the daylight potential in terms of providing circadian stimulus [45].

The view direction is an important factor that influences the amount of circadian light received by users of a space [44]. Zeng et al. (2021) evaluated the effect of the view direction (parallel or opposite to windows) and the distance from windows on the non-visual effects of daylight. The results showed that workstations near the windows, and with a view direction parallel to the windows, resulted in higher circadian stimulation. On the other hand, none of the workstations located at 4.5 m from the windows, with view directions parallel and opposite to the windows, met the required circadian lighting thresholds [46].

4. Architectural Design Factors Affecting Daylighting

Although estimating the role of architecture in contributing to the non-visual effects of light is not an easy task, architectural design should consider strategies to enhance the occupants' exposure to circadian light in buildings [9,41]. Architectural factors, such as the window area, surface reflectance, orientation, room geometry, glazing material, etc., alter the daylight and artificial light characteristics inside buildings [6,30,41,47,48]. Regarding daylight, architectural design should control the quality, quantity, and timing of daylight exposure to maintain building users' physical and psychological health [26,30]. The process begins with schematic and conceptual designs defining buildings' forms, locations and orientations, windows' locations, shapes, and areas, and spatial zoning. The design development stage specifies more details such as the design of shading devices, glazing technologies, surface reflectance, and integration details of natural and electrical light [30].

Traditional daylighting practices stipulate the use of neutral wall colors and neutral glazing, and they discourage the use of tinted glazing and dark wall colors [49]. However, the built environment shows many conflicting design practices based on personal and cultural preferences and weather-related purposes [48]. For example, people apply different films and coatings on windows to meet desired requirements, such as minimizing heat transfer between the exterior environment and the building's interior [50].

Architectural spaces modify the characteristics of light (i.e., the spectrum, intensity, and directionality) that influence the circadian entrainment [41]. The spectrum of daylight inside buildings is filtered due to several reasons, such as weather conditions [44], air pollution, humidity [51], external obstructions, the finishing of surfaces [25,41,47,52], plants, shading devices [26,53], glazing type [54], and the spectral reflectance of the interior surfaces [47]. The spectral composition of light reaching the eyes depends not only on the spectrum of the light source, but also on the optical characteristics of internal surfaces and furniture [41]. The SPD of daylight after entering buildings must be known to precisely evaluate the contribution of daylight in terms of the visual and non-visual comfort of occupants [51].

A recent review by Bellia and Fragliasso (2021) classified the architectural factors influencing indoor lighting characteristics into four categories, including urban design, architectural design, technological design, and interior design, based on the design scale. The study linked each design scale to the indoor lighting spectrum, quantity, spatial pattern, and temporal pattern (i.e., the timing of daylight access to interiors). These lighting characteristics are known to be essential to circadian entrainment. The urban scale affects the light levels, spectrum, and temporal patterns by defining the location of buildings within the urban context, their shape and dimensions, their orientation, and external obstructions [41]. For instance, daylight access to buildings is highly related to the height and distance between them (Figure 2). Furthermore, building orientation has a role in controlling the spectral composition of daylight inside buildings. The spectral composition of daylight entering buildings from eastern façades in the morning is different from that irradiating western facades at dusk [25].

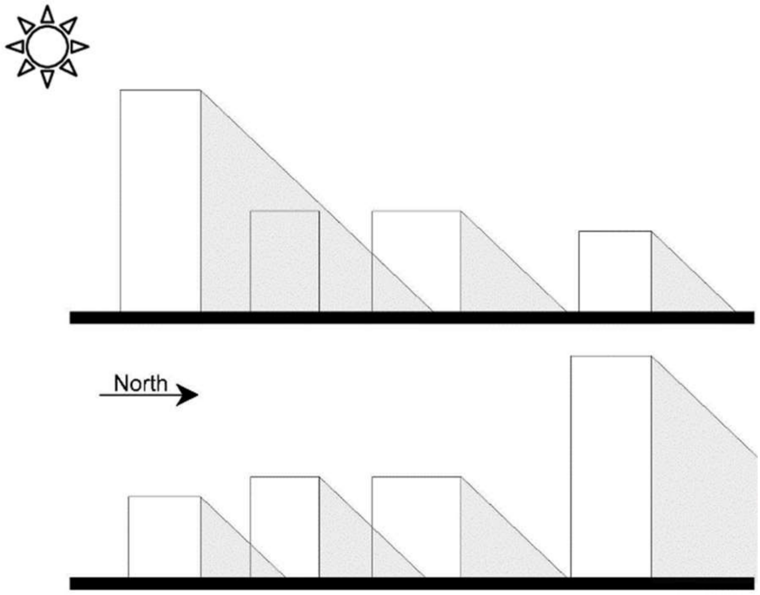

Figure 2. In the Northern hemisphere, placing tall buildings on the south of urban fabric prevents daylight access to low buildings.

The architectural scale defines the parameters of dimension and shape of both spaces and apertures, as these factors influence the amount of daylight admitted to spaces, as well as its distribution [11,12,25,55]. For example, the lighting distribution in a rectangular space with windows on the long side is more uniform than a space with windows on the short side, as seen in Figure 3 [41]. The technological scale looks into the characteristics of transparent [48,53] and opaque materials [11,12,55–57] that constitute the building envelope, as well as the façade materials [52]. The characteristics of the envelope affect the daylight level, spectrum, and distribution inside architectural spaces. At the same time, façade materials and external obstructions alter the spectral characteristics of daylight depending on its spectral reflectance [25,41,58].

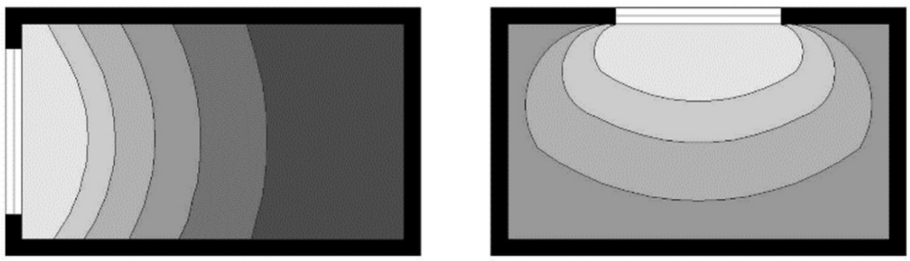

Figure 3. Luminous uniformity in rectangular space in relation to window placement within different facades.

The interior design decisions alter the characteristics of both daylight and artificial light. The color of the internal surfaces is an essential factor to consider. For example, spectrally selective surfaces (i.e., colored surfaces) modify the spectral composition of light [47,58,59]. Furthermore, walls of light colors will increase light levels compared to walls of dark colors [55,57]. The location of furniture is another important determinant of occupants' circadian entrainment [12]. Furniture placement controls the view direction of space users, which in turn determines the quantity and quality of the circadian light received by occupants from both windows and luminaires. For instance, a person facing a window will receive more circadian light than a person facing a wall [41].

Vaz and Inanici (2020) conducted daylight-driven simulations within a simplified model office to study the effect of various architectural parameters on the circadian potential of spaces. The researchers used the term 'circadian potential' to define "the maximum percentage area in a given space that daylight provides 240 EML or more in a given environment" [45]. According to the WELL Standard, exposure to 240 EML sustained for a 4-hr period leads to full melatonin suppression and phase shifting in a human's circadian rhythm [60]. Among many architectural parameters, Vaz and Inanici (2020) selected six parameters that are relevant to standard daylighting practices: view direction, window head height, building orientation, shading devices, external obstructions, and room depth [45].

Simulations showed a strong correlation between viewer orientation and distance from the window to maximize the circadian potential. Changing the view direction alone resulted in a 58% change in the circadian potential of the investigated space. Simulations also showed a linear correlation between the windows' head height and the depth of daylight penetration, accounting for circadian stimulus. However, the results indicated that the effect is minimal compared to other factors. In addition, this linear correlation might result from changing the window-to-wall ratio (WWR) in simulated models. The researchers tested models facing south (control model), north, east, and west to evaluate the effect of building orientation on circadian potential. The results revealed that north-oriented windows decreased the circadian potential by 23%, while east- and west-facing windows decreased it by 16%, compared to the control model, which was expected for a building located in Seattle, Washington (Northern Hemisphere). External obstructions (surrounding buildings in this study) also caused a significant reduction in circadian potential. On the other hand, reducing the room depth increased the circadian potential through inter-reflections of the light [45]. The influence of windows, shading devices, external obstructions, surfaces' color and reflectance, space depth, and glazing properties on the non-visual effects of light are the most investigated among the architectural parameters.

4.1. Windows

The area, location, orientation, and geometry of windows greatly influence the amount and distribution of daylight admitted to spaces [30]. Larger windows were found to provide better circadian lighting. Acosta et al. (2017) and Acosta et al. (2019) used the circadian stimulus autonomy metric (CSA) to evaluate the effect of window area on circadian entrainment in hospitals [12] and educational spaces [11]. Circadian stimulus autonomy is defined as "the percentage of days in the year when Circadian Stimulus (CS) is equal to or greater than 0.35 for at least 1 h in the morning" [12]. Acosta et al. (2019) simulated the effect of three window sizes on circadian stimulus autonomy and observed a linear tendency between window area and CS. A WWR of 60% showed a 15% CS increase compared to a medium-sized window (WWR = 45%), which in turn showed a 14% CS increase compared to a small-sized window (WWR = 30%) [11].

Acosta et al. (2017) compared the effect of various WWR on CS. Again, larger windows provided higher CS. Figure 4 shows that the resulting CS values and window areas are not directly proportional. The study compared WWRs of 10%, 20%, 30%, 40%, 60%, and 80%. It was noticed that WWRs of 60% and 80% provide similar CS values; thus, there is no significant advantage of having very large windows. In addition, the results revealed that a WWR of more than 40% allows an evenly distributed CS [12]. Aguilar-Carrasco et al. (2021) compared the effect of 20%, 30% and 40% WWRs on the CS. A WWR equal 40% increased the room area, with a sufficient CS value, by approximately 50% of the 30% WWR. However, a WWR of 30% provided an appropriate CS value near the window, while a WWR of 20% did not provide sufficient circadian response at all [61].

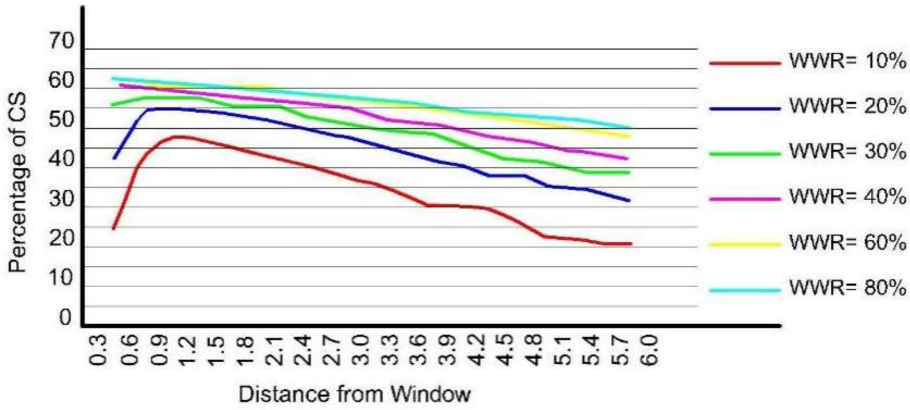

Figure 4. The relation between several WWRs and resulting CS values (adapted from [12]).

A window is considered most efficient when it faces the largest portion of the sky. Thus, large windows allow the occupants of a space to see a larger portion of the sky and bring more daylight into the space. Toplighting apertures with horizontal glazing are considered the most efficient apertures since they face the full sky hemisphere (Figure 5). However, toplighting systems are not very common because they are not beneficial in multistory buildings, except for the upper floor [30]. Zeng et al. (2021) measured the non-visual effects of light in office spaces located in Chongqing, China. They reported that the window orientation determined the circadian stimulation trends under a clear sky, but not an overcast sky. The measured non-visual effects decreased gradually on east-facing office space, suggesting that east-facing offices might be the most beneficial for humans' circadian systems [46].

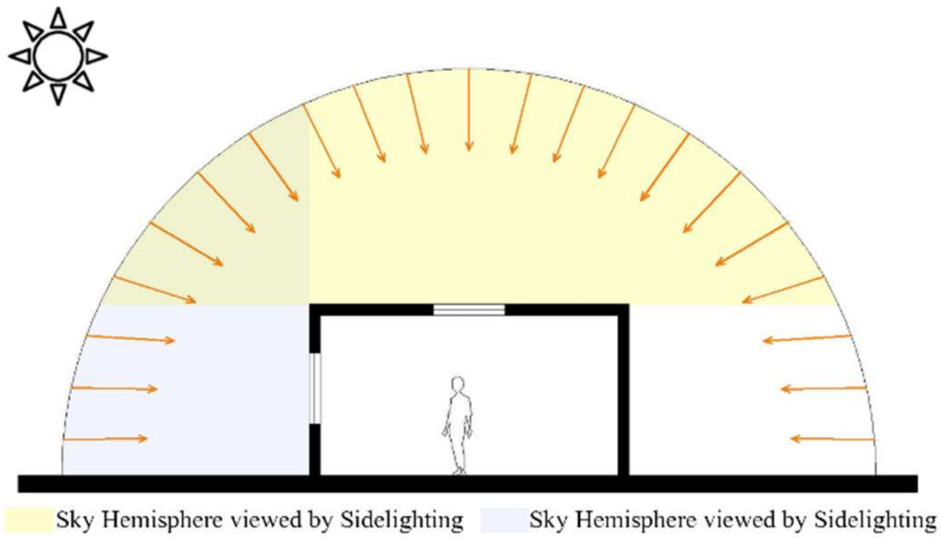

Figure 5. The sky hemisphere portion viewed by toplighting and sidelighting.

Windows should be designed based on the predominant sky type. Skies are generally classified into three major types based on the cloud cover or the percentage of cloudiness. The clear sky type has 0–30% cloudiness (or 0.3 cloud cover). Without counting the solar component, this sky type has a luminance ratio of 1:3 zenith to horizon. A partly cloudy sky has 40 to 70% cloudiness (or 0.3–0.8 cloud cover). The luminance distribution in the partly cloudy sky has a dynamic range due to the increased percentage of clouds, which causes difficulty in controlling sky luminance admitted to the space with simple shading devices such as those used in clear sky conditions. The overcast sky type has 80–100% cloudiness (or 0.8–1.0 cloud cover). The luminance distribution in the overcast sky is about 3:1 zenith to horizon. The predominant sky type affects decisions related to the window's location. Two windows of the same area with different locations within the façade will admit different daylight levels into the space. A higher window will bring more daylight into the space in case of an overcast sky (the sky luminance ratio of the zenith to the horizon is 3:1) (Figure 6a). In comparison, the lower window will bring more daylight in the case of the clear sky as the sky luminance ratio of the zenith to the horizon is 1:3 (Figure 6b) [30].

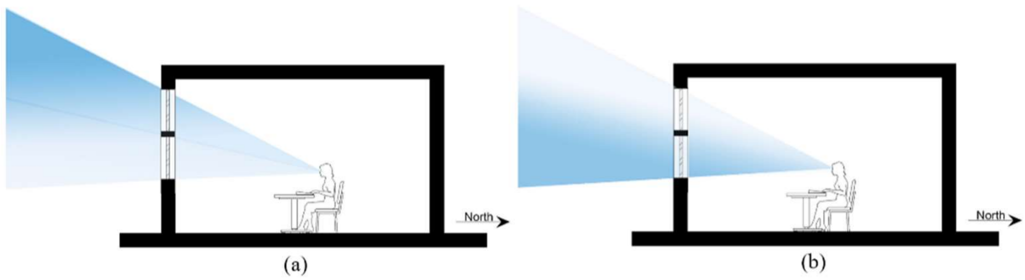

Figure 6. (**a**) Higher window admits more daylight under overcast sky; (**b**) lower window admits more daylight under clear sky.

4.2. Shading Devices and External Obstruction

Vaz and Inanici (2020) tested the effect of four shading devices on the circadian potential: 1.4 m deep continuous overhang, 10 cm horizontal blinds (spaced 9.5 cm apart), and an electrochromic glass of 6% and 18% transmittance. The results revealed that shading devices that significantly modify the color and/or intensity of daylight admitted through windows have an adverse effect on circadian potential. Thus, continuous overhang and horizontal blinds had minimal effect on circadian potential (6% and 2% reduction, respectively), while electrochromic glass had a significant impact (up to 58% reduction) [45]. Parsaee et al. (2020) investigated the effect of shading panels' (SPs) characteristics (color, reflectance, orientation, and openness) on the visual and non-visual responses of occupants [62]. The researchers used the melanopic to photopic units (M/P) to represent the potential visual and non-visual responses to light. M/P = 1 describes the light source that has equal melanopic and photopic intensities, and thus, equal visual and non-visual effects. When M/P > 1, the light source has higher melanopic intensity; when M/P < 1, photopic intensity is higher than melanopic intensity [63]. The results showed that bluish SPs could increase the intensity and distribution of melanopic luminance and CCT inside spaces, while reddish SPs could increase the photopic luminance intensity and distribution and reduce CCTs. The reflectance of the SPs affected the magnitude of the color impact. Matt SPs resulted in more impacts on the M/P ratios, intensity, distribution of photopic and melanopic units, and CCTs compared to glossy SPs. Horizontal SPs significantly obstructed direct sunlight penetration into the space for the south-oriented window compared to the vertical SPs. In addition, it greatly affected the M/P ratio, intensity, distribution of photopic and melanopic units, and CCT all over the space, in contrast to the vertical SPs. Reducing the openness between the panels increased the impacts of vertical SPs on sunlight penetration and melanopic and photopic luminance. However, the impacts of vertical SPs were always lower than the horizontal SPs in similar configurations.

External obstructions affect the amount of daylight entering a space [30,41] and they modify daylight SPD [25,41]. Hartman et al. (2014) evaluated the effect of obstacles colored in light brown on SPD and CS levels. Placing an obstacle in front of the tested model decreased illuminance and reduced CS levels [58]. A similar experiment was conducted to evaluate the influence of white-colored and dark-red-colored shading obstacles on the circadian efficacy of daylight. The results showed that dark color shading obstacles have a negative impact on the circadian efficacy of indoor spaces [52].

4.3. Surface Color and Reflectance

When the circadian effects of light are investigated, evaluation is conducted based on corneal illuminance, not illuminance at the work plane [41]. The overall corneal illuminance reaching the occupant's eyes is divided into two parts: direct illuminance arriving directly from light sources to the eyes, and indirect illuminance caused by inter-reflected light that underwent at least one reflection in the space before reaching the eyes (Figure 7). The preferred ratio of direct/ indirect parts is not the same for visual and non-visual circadian effects. Energy efficiency calls for a higher percentage of direct light for visual tasks, while a higher percentage of indirect light is preferred for non-visual effects and to avoid uncomfortable glare. Surface reflectance is believed to be an important factor affecting indirect corneal illuminance in both daylighting design and artificial lighting design [48]. The reflectance properties of the interior environment, causing inter-reflections of daylight inside the space, play a role in modifying the spectrum of daylight [47,64]. Therefore, attention should be paid to the interior surfaces' finishing colors and reflectance [41].

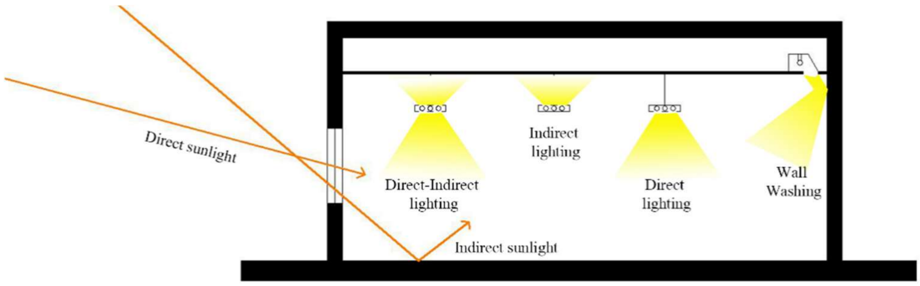

Figure 7. Different lighting schemes for indoor environments, provided by natural light and artificial light.

Designing a proper indoor luminous environment demands an accurate prediction of the space color perceived by occupants [65]. Although the light color is an important factor in achieving the desired non-visual requirements, the resultant lighting effect is not always the one intended by designers. The SPD of a light source (luminaire or daylight) would be similar to the spectrum received by an observer's eyes if the interior finishing color is achromatic. However, if the interior finishing color is chromatic, the spectrum received by the observer might be different from the intended design [66]. A research group from the Slovak University of Technology in Bratislava, Slovakia performed three studies, using scale models representing an office, to evaluate the effect of several surface colors of a room on the circadian stimulus [47,58,59]. Point-in-time daylight measurements were performed using a spectroradiometer and/or Daysimeter under overcast sky conditions. Ref. [47] compared three models (yellow, orange, and red walls) with a reference model (white walls). It was found that the corneal illuminance in the reference model is twice the illuminance in the colored models. Yellow, orange, and red walls reduced the CS values by 12%, 9%, and 6%, respectively. Applying dark-blue deficient colors on interior surfaces decreased the circadian efficacy, especially in the deeper parts of the models [47].

Ref. [58] compared yellow, light gray, and blue walls with a white-wall model (reference model). All models reduced the CS values compared to the reference model, with yellow being the worst, followed by blue and gray. Although the yellow-colored model had the best performance in terms of visual requirements (after the reference model), it filtered out the blue component of the daylight spectrum and, thus, had the worst performance in terms of CS. The blue and gray models registered lower CS values, but they provided more uniform values across the model. In all cases, the measurement points directed toward the walls registered lower CS values than those directed toward the window. The study detailed in ref. [59] was constructed along similar lines to [58], but it was conducted in winter instead of summer, and it gave the same results. Hartman et al. (2015) compared the effect of colored internal surfaces on the human biological response [64]. White-colored surfaces provided more than 50% greater effective biological stimulation than colored surfaces (dark brown, yellow, and orange). The improper choice of interior surface colors can decrease circadian stimulation in spite of good performance in terms of visual requirements [59,64]. In addition, walls of different colors having the same visual reflectance might induce different circadian potentials [48]. For example, a blue wall with the same visual reflectance as a red wall induces higher circadian values [54].

A recent study demonstrated that colors of internal surfaces also affect circadian stimulation under artificial light [65]. Kim et al. (2017) developed software called the Color Quality Assessment Tool (CQAT) that considers the SPD of luminaires, spectral reflectance of the interior surfaces, and the position and view direction of the occupant [66]. The tool was used to calculate the spectral color property of indoor luminous environments. It was validated in a later study by comparing the tool's results with full-scale mock-ups [67]. Ref. [66] used red and blue walls distributed in different scenarios (all walls are colored, one wall is colored and the rest are neutral, etc.), while study [67] used neutral floor and ceilings with colored walls (blue, red, and gray). Ref. [66] found that the direct component of light from the luminaire incident at the observer's eyes equals 70% of the corneal light, while the indirect component due to surface inter-reflections is equal to 30%. This ratio was validated using mock-ups, confirming the role of interior finishes in altering the spectral reflectance of light delivered by luminaires.

Interior surfaces and furniture reflectance are also important factors in improving corneal illuminance [3,56,57,68]. Acosta et al. (2017) performed simulations for a hospital room to define the relation between interior surface reflectance, WWR, CS, and CSA [12]. The simulated rooms were located in London, UK, and Madrid, Spain. It was found that wall reflectance controls the WWR needed to provide the CS and CSA required in the room. For instance, if the room located in London had high-reflectance walls, 40% WWR would have been needed for a patient lying down (30% for a sitting up patient) to provide a CS value higher than 0.35 in the entire room. If the room had low reflectance walls, even an 80% WWR would not have been enough to provide the same CS value for a lying patient, while a 40% WWR would have been sufficient to meet the threshold for a sitting patient. Another study conducted in educational spaces evaluated the effect of desk reflectance on CS and CSA metrics, in cases of bright and dark inner surfaces of classrooms. The results demonstrated that a classroom with low reflectance walls could barely provide a proper CS value, regardless of window size, location, or orientation. The study also showed that a white desk could increase the average CS by 100–255% compared to a light wood desk, and by 20–50% compared to a light blue desk [11]. Safranek et al. (2020) also evaluated the effect of white versus wood-finish desks in classrooms and showed consistent results [3].

Anderson et al. (2013) used simulation to examine the effect of various design parameters on daylight exposure and circadian stimulation in existing row houses located in Boston. The results showed that the most important parameter to provide sufficient light is the presence of highly reflective walls. White paint alone resulted in a 15% increase in daylight autonomy, meaning that there would be 55 more days a year during which the circadian light threshold would be met [55]. Improving the interior surface reflectance is an easy and cheap way to increase the indirect corneal illuminance in existing buildings. In addition, it is more energy-efficient, from lighting and HVAC perspectives, when compared with increasing the WWR [57] or increasing the luminaire flux [69]. Dai et al. (2018) indicated the benefit of having a high-reflectance ceiling and directing the luminaire flux towards it. Directing the initial flux uplight instead of downlight results in a higher level of—and much more uniform—indirect corneal illuminance [69].

4.4. Space Depth

When possible, daylight should be prioritized over electric lighting to illuminate interiors due to its health benefits [70,71]. However, occupants might draw blinds when sunlight penetrates rooms to prevent uncomfortable glare, thus eliminating daylight from rooms. Typically, as the distance from windows increases, the daylight levels inside rooms drop quickly. Daylight levels are always low about 3–4 m away from windows, even on sunny days [10]. Spaces can be seen as having two daylit zones depending on the space depth: a primary and a secondary zone. The rule of thumb states that the depth of the primary zone is about equal to the window head height, while the depth of the secondary zone extends between 1- and 2-times the window head height, as shown in Figure 8 [30]. Allen and Iano (2017) mentioned that the depth is up to 2.5-times the window head height [72].

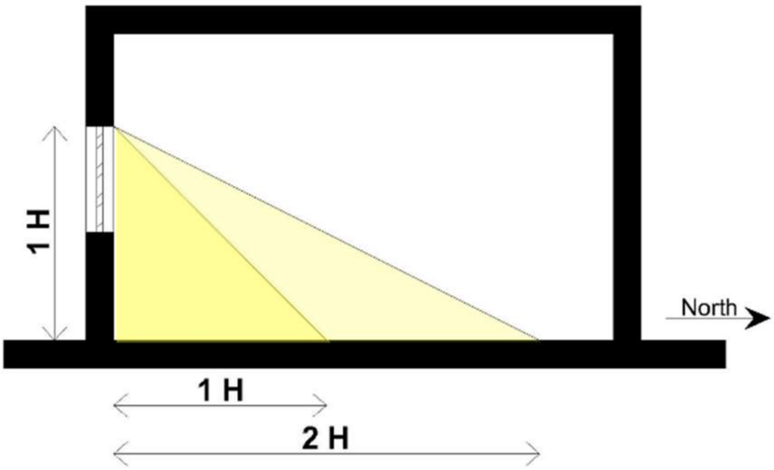

Figure 8. Window head height to light penetration depth rule of thumb.

Reinhart (2005) simulated spaces for a variety of façade orientations, geometries, and climates to validate this rule of thumb. The results supported the predictions made by the rule of thumb, relating the depth of daylit area adjacent to the facades to the head height of the windows. The depth of daylit zone extends between 1 and 2 times the window head height for a standard window with Venetian blinds, while the depth can go up to 2.5 times if the space does not have shading devices. The ratio also varies based on the glazing type used for windows [73]. Sidelighting can admit light from one wall or façade (unilateral) or two opposite sidewalls (bilateral). If the depth of the space exceeds the value recommended by the rule of thumb, the designer should consider adding a window(s) on another wall (i.e., bilateral sidelighting) [30]. Good daylit spaces require narrow-depth floor plans, which conflicts with the need to maximize the usable/rentable floor area. Bilateral sidelighting provides a suitable solution to solve this issue. Some floor plan configurations, such as courtyard floor plans, allow designers to use bilateral sidelighting by increasing the surface-to-volume ratio (S/V ratio), as in Figure 9. As the S/V ratio increases, daylight access to spaces increases as well [30]. Bilateral sidelighting can extend the depth of daylit area up to five-times the window head height [74].

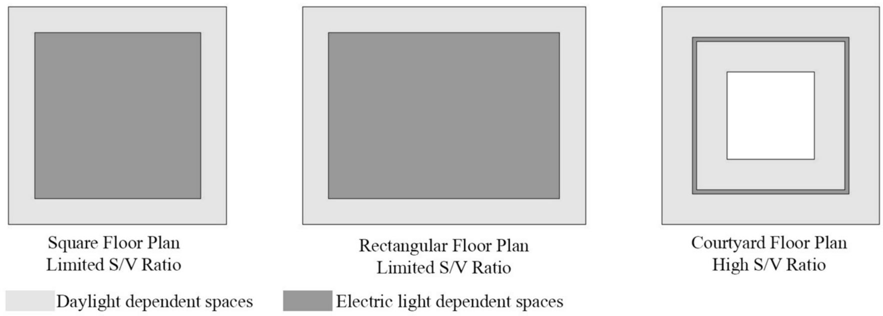

Figure 9. Increasing the S/V ratio provides better daylight inside spaces.

Aguilar-Carrasco et al. (2021) investigated the effect of the WWR in terms of providing suitable CS in a 24/ laboratory area. The results indicated a relation between WWR and light penetration into the space. A WWR of 40% provided sufficient CS at a depth of 1.5 H, while a WWR of 30% provided sufficient CS at a depth of 1 H [61]. Vaz and Inanici (2020) investigated the relationship between the room depth, the window head height, and the circadian potential of the space. Simulations were used to evaluate the effect of changing the window head height from 8 ft to 7 ft and 9 ft on meeting the circadian lighting requirements. The WWR was changed from 0.4 to 0.32 and 0.48 accordingly, while the windows' sill height was fixed. The results showed an increased light penetration for sensors meeting the assigned lighting thresholds with increased window head height. Daylight penetration increased by 8.5 ft, 5 ft, and 3 ft for the 9 ft, 8 ft, and 7 ft window head heights, respectively. The researchers stated that this increase might have resulted from the increasing WWR, not the window head height, and they found that the effect of increasing the window head height is minimal compared to other design factors. On the other hand, researchers showed that reducing the space depth could significantly increase the circadian potential of the space through inter-reflections [45].

4.5. Glazing Properties

Architects usually choose the glazing type in the design phase, and it is rarely changed during the lifetime of buildings; thus, it is essential to select the correct type of glazing [48]. Glazing transmittance participates in daylight inter-reflections inside spaces and plays a role in changing its spectrum [47]. Glazing material should have a minimal distorting effect on the daylight spectrum [26]; however, the importance of other design requirements, such as controlling solar gains, might compete with the necessity of admitting daylight without modifying its spectrum [53].

The color of daylight admitted into spaces through windows is highly modified by the glass surfaces coatings, glass tinting, interlayer tinting, or a combination of these. Daylight coming through tinted glazing can affect occupants' color perception undesirably and distort the colors of outdoor views [47,75]. Arsenault et al. (2012) conducted a study using a scale model to evaluate the effect of glazing color on daylight quality perception and alertness. The results indicated that there is a preference for daylight filtered through tinted glazing. Participants preferred bronze glazing compared to neutral and blue-tinted glazing. In addition, the study showed that glazing color caused a significant impact on alertness [76].

Chen et al. (2019) studied the effect of glazing color and transmittance on participants' mood, alertness, working performance, and satisfaction in the winter period. The study was performed in an office located in Beijing, China, with one south-facing window. The researchers used CS $\geq$ 0.3 as an indicator for good alertness and mood. The effects of seven types of glazing were investigated: clear, blue, bronze, gray, green, dark blue, and red. Self-reported satisfaction questionnaires showed a preference for glazing systems with higher transmittance and/or neutral color. The results demonstrated that dark blue glazing resulted in low CS values compared to other glazing types. CS values < 0.3 resulted in a significantly bad mood while increasing the glazing transmittance and/or decreasing its color saturation was beneficial in terms of improving the participants' moods [53].

Potocnik and Kosir (2020) used simulation to investigate the effect of glazing transmittance along with the spectral reflectance and color of interior walls on non-visual daylight conditions. Multiple combinations of wall colors and reflectance, and glazing colors and transmittance, were evaluated. The results showed that higher values of visible transmittance glazing and wall reflectance result in higher non-visual potential. The combination of low-e glazing with high transmittance and blue walls resulted in the highest non-visual entrainment, while the combination of bronze-tinted glazing and orange walls resulted in the worst entrainment. The researchers suggested using neutral glazing as a first choice. Blue-tinted glazing is recommended for overheating prevention in buildings, as it is the best alternative to neutral glazing in terms of non-visual potential [48].

Saiedlue et al. (2019) employed a simulation to investigate the daylight circadian potential admitted through different glazing systems, and the circadian efficacy delivered by various electric lighting systems. Three glazing types were applied to a south-facing window in a side-lit open plan office located in Minneapolis, Minnesota. The glazing types were clear glass, single-zone electrochromic glass (EC), and three-zone EC glass. Single-zone EC glass is completely either clear or tinted, while three-zone EC glass is segmented into three horizontal zones; every zone is cleared or tinted independently. The goal was to achieve a balance between the melanopic illuminance threshold (200 EML) and the photopic illuminance threshold (<1500 lx). The office was divided into three zones, A, B, and C, based on their distance from the window. The findings showed that clear glazing performed better than single-zone EC glazing and three-zone EC glazing in terms of circadian system potential, but it delivered very high levels of photopic illuminance. Three-zone EC glazing performed best in terms of balancing the melanopic and photopic illuminance. For electric lighting systems, blue LED luminaires met the melanopic illuminance threshold in all zones and for all view directions, while the EML values under the red and orange LED luminaires were negligible [77].

4.6. Summary

Evaluating the role of architecture in achieving non-visual lighting requirements is a complex task. A few studies addressed the influence of architectural factors on spaces' circadian potential; at present, however, each element's weight is not well understood. Studies evaluated the effects of different urban, architectural, and interior factors, including window size and orientation, window head height, external obstruction characteristics, shading device type, interior wall color and reflectance, furniture color and reflectance, glass color and transmittance, room depth, and building location. Studies also emphasized the importance of view direction and distance from windows in meeting the circadian illuminance threshold. Moving occupants' activities from core areas to closer distances to windows and arranging the furniture (e.g., desks in offices) towards windows can considerably increase the corneal illuminance.

Good daylighting conditions should satisfy both visual and non-visual lighting requirements. While circadian daylighting demands a considerable quantity of corneal illuminance, it should not cause overly high light levels, which would result in uncomfortable glare. A good way to achieve this is to increase the indirect illuminance inside spaces. Highly reflective interior and exterior surfaces (e.g., surrounding buildings, facades, and ground cover) play a major role in enhancing the daylight quantity and quality through inter-reflections. Thus, choosing proper reflectance values, for at least the internal room surfaces and furniture, is an important design decision. Painting walls with neutral colors, such as white and gray, is an easy and cheap method to increase circadian stimulus. On the other hand, painting walls with warm colors (e.g., red, yellow, and orange) negatively affects the circadian stimulus, especially when combined with bronze-tinted glazing. Increasing the glazing transmittance and/or decreasing its color saturation results in better non-visual lighting effects. Designers should always consider using neutral glazing first, followed by blue-tinted glazing, when overheating prevention is required.

Windows should be designed based on the predominant sky type. Designers should consider using larger windows that face a large portion of the sky to maximize daylight penetration. The higher head height allows daylight to penetrate deeper into the space, and thus, to increase the depth of the space where daylight is sufficient to meet visual and non-visual lighting needs. If deeper rooms are designed, bilateral sidelighting is better for use in helping daylight to penetrate deeper into rooms.

5. Human-Centric Lighting Design

Designers have always been asked to design "well daylit spaces", but the meaning of this description is not clear [30]. The requirements for visual performance are typically defined by guidelines and standards, while designers determine the required non-visual lighting effects (e.g., design objectives) during the design process [78]. For instance, the designer should decide whether the function of the space is to make the occupants feel relaxed or alert [79]. The Human-Centric Lighting (HCL) approach provides lighting solutions that consider occupants' physical and mental health in relation to the visual and non-visual effects of light [29,62,80]. These lighting solutions are also called integrative, biodynamic, and circadian lighting [70]. The main principle of this approach is that humans, in addition to their visual and non-visual needs being met, should be at the center of the design process [8,81,82]. HCL evaluates the photopic and melanopic lighting quality of spaces, as well as the color temperature affecting the visual and non-visual responses [62]. To date, there are no HCL-related ordinances or laws [83].

5.1. HCL Concept and Approach

The concept of HCL is derived from the evolution of the intensity and CCT of natural light throughout the day, and how it stimulates humans' circadian rhythms [83,84]. It is focused on manipulating light-related factors (i.e., intensity, spectrum, directionality, and duration) within the built environment to benefit human health and comfort [82]. HCL suggests full control of light to improve architectural spaces and their effect on humans' mood, cognitive performance, productivity, and satisfaction, especially in work environments such as offices and classrooms [80]. HCL is a holistic approach that considers architectural spaces and their characteristics (e.g., wall and furniture reflectance), people's rhythms and activities within these spaces, and the lighting technology available [8,80]. Houser et al. (2021) affirmed that lighting products claiming to be effective in improving peoples' performance, alertness, and sleep should be met with skepticism. HCL is not a product feature and is not only about buying products labeled as "integrative or human-centric lighting". For example, some lighting products tagged as HCL deliver more light in the short-wavelength part of the spectrum. These products might support the circadian rhythms of space users during the day, but they could lead to circadian disruption if viewed at night [82]. Hence, lighting products are only one part of the HCL design approach, and they need to be employed in the right way.

Houser and Esposito (2021) proposed a five-step design process, shown in Figure 10, to integrate HCL lighting design concepts into lighting design practices [29]. This process starts with defining users' tasks and activities within the space, as well as establishing when they use it, and their intended operational goals. Designers then have to determine if the space will have day-active users, night-active users, or both. Based on the type of user (or users) of the space, the designer has to decide if the space includes sleeping occupants, and if yes, the designer needs to define if they are day-active, night-active, or both. This step helps the designer to define lighting requirements, as sleeping occupants need darkness to promote sleep, while knowing if they are day-active or night-active determines if the space might require some modifications, such as window treatment to block sunlight. Step four states that published HCL guidelines and recommendations, such as recommended quantitative design targets, exposure times and durations set by WELL standards and the Underwriters Laboratory (UL), need to be reviewed. The last step put all information defined in the previous steps together to establish the design criteria and numerical design targets. Tradeoffs between visual and non-visual design goals can be decided in this step too. For instance, bright light during the day benefits the non-visual outcomes, but it might cause glare and conflict with energy codes.

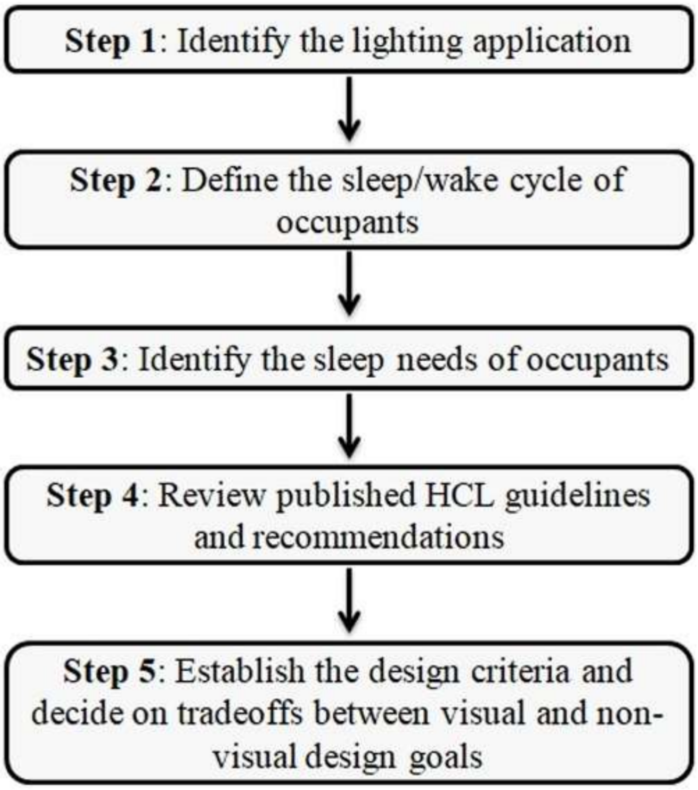

Figure 10. Design process proposed by Houser et al. (2021) for human-centric lighting.

Lighting inside buildings should provide suitable circadian lighting 24 h per day: high circadian lighting during the day, and low circadian lighting at night [82]. Although daylight is a circadian-effective light source that provides high light levels during the day and no circadian lighting at night, it is not necessarily true that daylight will always provide sufficient circadian stimulation in architectural spaces [85]. Light should reach the retina to induce circadian responses and start the phototransduction process [43]. Hence, artificial lighting has a crucial role in providing humans with lighting needs and supporting their health [29]. The challenge is to determine the "human's needs" of light to support her/his health, as it differs based on individual preferences, sensitivity, and experiences [86]. To be able to support visual and non-visual requirements, artificial lighting should be spectrally optimized to minimize the optical irradiance (i.e., optical power) at the cornea level, and it should deliver more vertical illuminance (E_V) at the eye level instead of horizontal illuminance (E_H) on the work plane, preferably through inter-reflections or indirect lighting [87]. According to manufacturers' data, direct–indirect distribution of luminaires provides the best E_V/E_H ratio, compared to the single use of direct or indirect distribution [78]. Higher E_V/E_H might cause uncomfortable glare; therefore, trade-offs between delivering effective corneal illuminance and glare formation should be considered [43].

In artificial lighting design, luminaire selection was found to be an important factor in achieving higher E_V/E_H for circadian benefits. Jarboe et al. (2020) simulated multiple luminaire types with different luminous intensities and SPDs. They found that linear pendants and troffers with some direct components are the most efficient luminaire types for circadian stimulation. The study also found that using vertically oriented luminaires and indirect light sources that reflect light off surfaces within spaces results in higher E_V/E_H. Calculations showed that a minimum E_V/E_H ratio of 0.65 would be necessary to achieve a CS target of 0.3, while the use of lower light levels was recommended for the work plane. Adding desktop luminaire directed towards desk user's eyes resulted in great circadian stimulation [43]. ThiGiang et al. (2020) compared the effect of using downlighting and uplighting on the provision of indirect light inside architectural spaces [88]. Downlighting and semi-direct lighting are common, but they have disadvantages, such as low illuminance uniformity inside spaces and the considerable contrast between luminaires and their surroundings. Uplighting makes use of ceiling and walls in reflecting light, making these surfaces supplementary light sources. The Chartered Institution of Building Services Engineers (CIBSE) and the Building Research Establishment (BRE) recommend using lighting fixtures that have an upward light and "wall washing" to maximize the reflected light from space surfaces (Figure 7) [89]. ThiGiang et al. (2020) found that the proper design of uplighting yields uniform bright surfaces, fewer glares within the space, and better luminous uniformity over the interior [88].

Rossi (2019) defined key features that make artificial lighting an effective circadian light. Artificial lighting should mimic natural light's dynamicity by changing its intensity and CCT during the day. To increase concentration and alertness, it should provide short wavelengths (i.e., cool CCT) for at least two times of the day: the first half of the morning (6:00–8:00 a.m.), and the first half of the afternoon (12:00–15:00 p.m.). Higher light levels should be used in these periods, while lower light levels and warm CCT should be used before the evening and at night [8]. Figueiro et al. (2016) and Busatto et al. (2020) explained that designers should not rely only on light sources' CCT. Designers should consider the SPD of the light, as light sources with the same CCT might give different circadian stimulation based on their SPD. SPD optimization is also required to produce the desired visual and non-visual lighting effects [68]. Furthermore, higher CCTs do not always mean higher circadian stimulation. For example, it was found that a 3500 K light source gives much less circadian stimulus than a 3000 K light source [78,79].

Light sources with more short wavelengths in their spectral composition effectively stimulate the circadian system [41]. Experts were not able to design interior lighting with a defined spectrum until the advent of LED technology [83]. Unlike traditional lighting fixtures, spectral tuning is now possible with the emergence of multi-channel LED luminaires. These luminaires allow the tuning of the SPD of light throughout the course of the day to achieve circadian benefits and deliver high visual performance [90]. In addition to their long-operating life and high energy efficiency, LEDs have some characteristics that make them helpful in designing circadian lighting. LEDs are available in different light CCTs and colors; they provide better control over light intensity, ease of adjusting the luminous flux, and electronic control of power supplies [8]. Studies proved that multi-channel LED luminaires mimicking daylight could entrain and enhance circadian rhythms [20,21]. Future artificial lighting should combine visual and biological benefits [8]; however, a 24-hr artificial lighting solution would be hard to implement due to high budget and energy regulations [10].

5.2. The Effect of HCL on Energy Consumption

Daylighting, accompanied by energy savings, is considered to be the basic method to satisfy the HCL design requirements. Zeng et al. (2021) investigated the efficiency of daylight in providing non-visual lighting and energy-saving benefits. The results showed that spaces with good daylighting conditions provided sufficient non-visual lighting energy-saving potentials of 50%, compared to windowless spaces [91]. Aguilar-Carrasco et al. (2021) investigated the effect of daylight and electrical light integration on CS and energy use. The study used different window sizes, orientations, and two CCT values (2700 K and 5700 K); under different sky conditions. The results reported energy savings of between 21 and 80% in the summer and up to 60% in the winter [61].

Interior lighting is generally designed to provide visual performance. Artificial lighting can provide sufficient circadian lighting by increasing the power of luminaires or spectrally tuning the light [69]. Higher lighting levels are required to meet the recommended values for the circadian metric, which negatively affects the energy efficiency of lighting [43,87]. A study reported that the required corneal illuminance level to meet a CS $\geq$ 0.35 is 233 lx from daylight (D65 spectrum), 575 lx from 4000 K fluorescent lamp FL11, 387 lx from 5000 K FL10, and 266 lx from 6430 K FL1 lamps [87]. However, the corneal illuminance indoors can be much less than these values. Safranek et al. (2020) investigated the potential energy impacts of applying recommended circadian lighting design targets in an open office and a classroom [3]. The results of 45 simulation scenarios showed that energy use might increase by 10–100% to meet circadian lighting design recommendations (e.g., the recommendations of the WELL standards), due to using additional luminaires or increasing luminaires' light levels. Therefore, most of the recent research developing artificial lighting is working on improving the energy performance and color qualities of solid-state light, such as LEDs [18].

Employing dynamic or tunable light is another method to provide sufficient circadian stimulation. Lighting technology today is witnessing a transition from luminaires with fixed light intensity and CCT, to dynamic LED luminaires with tunable intensity, SPD, and CCT [92]. The ipRGCs are sensitive to short wavelength light, with a peak a round 480 nm [91]. Optimizing the SPD of light sources to have more short-wavelength in its spectrum to entrain the circadian system is possible with LED technology. Spectral optimization of LEDs can be used to achieve different goals, such as energy efficiency, circadian stimulation, and better color quality [93]. Researchers have been optimizing LEDs for years, aiming to improve energy efficiency. To compare, the average luminous efficacy of white-LED used today for general lighting is about 150 lumen/watt (lm/w), compared to 26 lm/w and 60 lm/w for incandescent and fluorescent lamps, respectively [94]. The role of LEDs in HCL is crucial due to the SPD flexibility that permits tuning the light for sufficient circadian entrainment, color quality, and energy efficiency [87,95,96]. However, the complex relationship between these three aspects and required tradeoffs has not yet been well investigated. Most studies focus on one or two aspects only at a time [93].

To satisfy non-visual light needs, studies recommend dynamic CCT and illuminance levels for 24 h dynamic artificial lighting designs by taking the daylight variability as a reference. A color temperature range of 3300–8000 K is inspired by daylight [97]. Lights with high CCT efficiently provide corneal illuminance and alerting effects while reducing energy consumption, especially when daylight is not present [91]. Using a CCT of 8000 K, a corneal illuminance of 187 lx is needed to achieve a CS target of 0.35 [87]. Luminaires with lower CCT require increased light levels to meet the circadian metrics and induce alerting effects, which means higher energy use [3,61]. However, many efforts have been dedicated to developing energy-efficient-low-CCT lights to use at night or in spaces where a relaxing effect is required [98].

Saw et al. (2020) stated that the problem with research aiming to provide circadian stimulation or healthy lighting is that it ignores the practical side of the optimized designs for commercialization needs. Saw et al. (2020) proposed a multi-objective optimization approach, using a genetic algorithm, to prove that it is feasible to have a practical design of LED luminaires, which are commercially realizable, satisfy non-visual needs, provide high visual quality, and have higher energy efficiency than typical commercial white-LEDs [90]. Research on the topic of HCL and energy efficiency is still at its early stages, and no conclusive evidence, nor enough studies, are available to define the impact of HCL designs on energy use.

6. Circadian Lighting Design: Standards and Recommendations

Traditional lighting design standards and practices were developed to fulfill humans' visual needs prior to the awareness of light's role in stimulating the circadian system [15,49]. Hence, these standards and practices target only the aspects of the visual domain, such as visual performance and comfort, using visually related quantities (e.g., illuminance, luminous flux, etc.) [49,99]. Current standards do not consider the non-visual effects of light [7]. For several decades, illuminance on the work plane has been the most critical parameter in indoor lighting design [69]. On the other hand, the non-visual effects of light are related to eye-level vertical illuminance (i.e., corneal illuminance) [48,50]. Traditional standards define minimum horizontal illuminance values, while very few require vertical illuminance values [69]. The European standard EN 12464-1 was the first to require vertical illuminance values. The standard requires an average cylindrical illuminance (i.e., average vertical illuminance) to be $\geq$50 lx in activity areas (i.e., areas within which specific activities are carried out) and interior spaces, and $\geq$150 lx in spaces where visual communication is essential (e.g., offices and teaching rooms), at the height of 1.2 m for seated people and 1.6 m for standing people [100]. According to recent studies, the required corneal illuminance, in general, is much higher than what is achieved or recommended by traditional lighting design practices [48,50].

Despite the non-visual response functions established by research in neuroscience, almost all lighting standards, recommendations, and measuring devices are still based on the photopic luminous efficiency function, V(λ) [25,101]. This function is based upon studies conducted about a century ago, aiming to measure the visual sensitivity of human eyes toward different wavelengths [102]. The problem with V(λ) is that it reflects the spectral sensitivity of only two, out of five, photoreceptors in the retina: the long-wavelength and middle-wavelength cone photoreceptors (L-cone and M-cone, respectively) [101,102]. V(λ) is not the best function to build on for standards formulation, as it does not represent the overall sensitivity of human eyes to electromagnetic radiation. For this reason, Rea (2015) proposed a universal luminous efficiency function, U(λ), as shown in Figure 11. U(λ) is based on the spectral sensitivity of the five photoreceptors in the human retina (short-wavelength cone, S-cone, L-cone, M-cone, rods, and the photoreceptors for the non-visual system: intrinsically photosensitive retinal ganglion cells and ipRGCs), covering the visual and non-visual response functions [101].

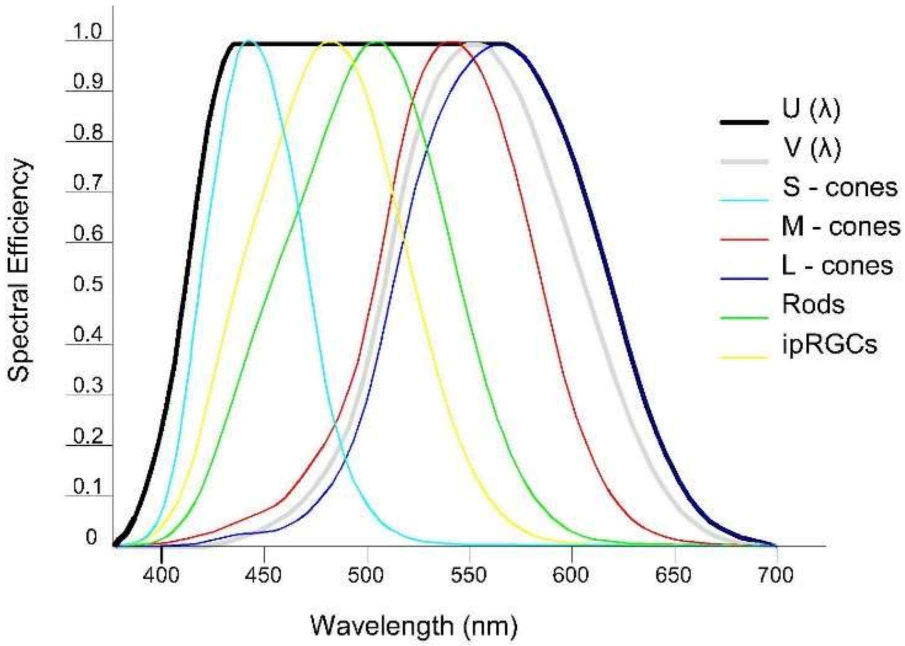

Figure 11. The spectral efficiency function of U(λ), V(λ), and the known photoreceptors (adapted from [101]).

National bodies recently started to establish detailed rules, recommendations, and guidelines for circadian lighting, such as Illuminating Engineering Society (IES) publications in the United States (e.g., IES TM-18-18 2011 and IES/ANSI RP-29-16 2017), and the German technical report DIN SPEC 67600:2013-04 "Biologically Effective Lighting—Planning Recommendations" [103,104]. Although a wide range of vertical illuminance values was proposed/recommended, there is no consensus on the quantity and quality of light and exposure duration that are sufficient to entrain the circadian system [15,48,69,105]. Furthermore, there are no studies to date that investigate the interaction between these factors [43]. Few circadian metrics/models were proposed in recent years to evaluate lighting's circadian impact. The most popular and frequently cited in the literature are the Circadian Stimulus (CS) [106–109], and Equivalent Melanopic Lux (EML) [110,111].

6.1. Circadian Stimulus Metric

The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute developed the circadian stimulus metric depending on the model created by Rea et al. (2005) [48], which in turn is based upon published studies in neurophysiology and neuroanatomy on circadian phototransduction [106]. Phototransduction is the process by which ipRGCs convert light energy into neural signals [112]. CS metric quantifies light efficiency in stimulating the circadian system, measured as melatonin suppression after 1-hr of nocturnal light exposure and assuming a 2.3-mm-diameter pupil [43,106]. The melatonin hormone is a well-known marker for the circadian system [113]. According to the model, the maximum melatonin suppression achieved after 1 h of light exposure is 0.7, whereas a value of 0.3 in the morning is sufficient to promote circadian entrainment [114].

CS value (unitless) expresses the percentage of melatonin suppression, which according to this model, ranges between 0 and 70%, or 0.7 [108]. The CS model first calculates the Circadian Light (CL_A), proposed later by Rea et al. (2010), as a counterpart to illuminance [109]. CL_A is the spectrally weighted irradiance at the cornea level, and it depends on the spectral efficiency functions of ipRGCs, rods, and cones [108,109]. It is measured at the cornea level using a head-worn device called Daysimeter [109]. CL_A is then converted to CS using the following equation [107]:

$$CS = 0.7 - \frac{0.7}{1 + \left(\frac{CL_A}{355.7}\right)^{1.1026}} \tag{1}$$

In 2016, LRC also developed a CS calculator [115] to help lighting professionals and designers select light levels and sources to increase the circadian light exposure efficiency in buildings at the proper time (i.e., during the day). The CS calculator provides CS and CL_A values for various lighting sources and can calculate CS values for user-supplied light source spectrums [78]. According to studies on teenagers, office staff, Alzheimer patients, and healthy adults, a CS value of at least 0.3, for at least 1-hr in the early part of the day, is effective for improving circadian entrainment, sleep quality, mood, alertness, and behavior [53,78,105,116]. Acosta et al. (2017) proposed a CS level of 0.35 as "sufficient to promote daily entrainment" in hospital environments [11], while Figueiro and Rea (2016) reported that a CS value of 0.25 for 2 h per day would be sufficient for maintaining circadian entrainment [8]. Although a substantial body of research on circadian lighting exists, an absolute minimum value of circadian light (CL_A) has not yet been specified [48]. This is due to the influence of many factors, such as race and age, which should be considered. A higher value of CL_A during the day is generally better for circadian stimulation [51].

It was reported in the literature that the CS metric has some limitations. The CS metric does not take the temporal aspects of light (e.g., light exposure duration, timing, and history) into consideration. It is only based on melatonin suppression, ignoring all other non-visual effects of light [7]. As circadian photoreceptors, ipRGCs, are most sensitive to blue (short wavelength) light, CS failed to explain the impact of red (long wavelength) light on the circadian system. Red light was found to affect the circadian system by increasing alertness without suppressing melatonin [117–120]. In addition, the CS metric considers melatonin suppression and phase-shifting as proxies. Phase-shifting, a non-visual effect of light exposure, is delaying or advancing the time when peak melatonin production occurs [121]. However, a recent study found that the relation between melatonin suppression and phase-shifting is non-linear, and one should not be used as a measure to the other [122]. It should be noted that despite the consistency of CS metric with the scientific literature in neurophysiology and neuroanatomy, and validation by many field studies, CS has not been sanctioned by standards organizations [3,43].

6.2. Equivalent Melanopic Lux Metric

There are, generally, two methods to quantify the non-visual stimulation efficiency of light: one based on nocturnal melatonin suppression [53,78,105,116], and another based on the spectral response of the photopigments in photoreceptors [71,94]. The equivalent melanopic lux (*EML*) metric is based on the melanopic response of ipRGCs photoreceptors, with a peak at 480 nm [94]. The term "melanopic" expresses the effect of light on ipRGCs [123], coming from "melanopsin", the photopigment in ipRGCs [110]. Melanopsin absorbs light energy when the retina is exposed to light, while ipRGCs send neural signals to the brain's pacemaker, suprachiasmatic nuclei (SCN), to regulate melatonin production [107].

The ipRGCs spectral efficiency function determines EML by weighting the SPD of light sources [124]. The metric was introduced by Lucas et al. (2014) [111], based on "the melanopic spectral efficiency function" proposed by Al Enezi et al. (2011) [110]. According to equation (2), *EML* is calculated by multiplying photopic illuminance measured at cornea level (*E*, lx) by a melanopic ratio (*R*, unitless), representing the luminaire efficiency in suppressing melatonin, where *R* ranges between 0.45 and 1.70 [29].

$$EML = E \times R \tag{2}$$

Light sources with higher CCT yield a higher value of *R*, and thus, a higher *EML* value [29]. The *EML* metric helps to differentiate the circadian effect of light sources that have the same visual effect [15]. For instance, incandescent lights that deliver 200 lx to a space produce 108 *EML*, while daylight delivering the same quantity produces 220 *EML*, pointing to higher circadian efficiency of daylight [79].

The commercial organization "International WELL Building Institute", which has a lighting-related category, adopted the *EML* metric to assess the circadian aspects of lighting design [52]. Although the application of WELL standard thresholds is not mandatory, buildings that have received WELL certificates have better lighting [83]. The WELL standard addresses the light intensity, timing, and duration necessary to entrain the circadian system in work areas, living environments, breakrooms, and learning areas. The most recent version of the standard requires at least 200 *EML* between 9:00 a.m. and 1:00 p.m. for every day of the year and at 1.2 m for at least 75% of workstations. This value can be obtained by daylight, electrical light, or a combination of both. The other option is providing all workstations with 150 *EML* at eye level, using electrical light. Living environments should provide at least 200 *EML* during the day, measured in the center of the room at the height of 1.2 m, while night lighting should provide a maximum of 50 *EML*, measured at 0.76 m height. Breakroom's lighting should be at least 250 *EML* at 1.2 m height, while learning areas should provide a minimum of 125 *EML*, for at least 75% of desks, and at 1.2 m height for 4 h per day for every day of the year [52].

Rea et al. (2012) argued that all known photoreceptors, not only ipRGCs, have input to circadian phototransduction; hence, the *EML* model should not be used separately to express lightings' circadian effect [108,111]. In addition, *EML* metric is not compliant with the International System of Units (SI). Therefore, the International Commission on Illumination (CIE) introduced a modified form of *EML* metric that is SI-compliant and defines the spectral sensitivity functions, metrics, and quantities to describe the ability of light in stimulating the five photoreceptor types that contribute to the non-visual effects of light. The International standard CIE S 026/E:2018 uses a compliant SI quantity instead of EML, named melanopic equivalent daylight illuminance (melanopic EDI or *mel-EDI*), expressed in lux [71]. *EML* is related to *mel-EDI* as follows [29]:

$$EML = mel.EDI \times 1.103 \tag{3}$$

Melanopic EDI is based on standard daylight (D65), described in CIE 015:2004 [125], as a reference source, and it expresses the quantity of daylight that provides the same melanopic irradiance as the test source [103]. For example, a mel-EDI of 150 lx denotes that the light source evaluated produces the same of melanopsin-activating light as a 150 lx of daylight at 6500 K. Mel-EDI is calculated by multiplying the photopic illuminance (E) by the melanopic Daylight Efficacy Ratio (melanopic DER or mel-DER), where mel-DER ranges between 0.40 and 1.60 [29]. CIE does not specify quantities of required mel-EDI; however, it recommends high mel-EDI levels during the day and low mel-EDI levels in the evening and at night [70]. In 2020, CIE launched a toolbox to support the use of CIE S 026/E:2018 [126].

The Second International Workshop on Circadian and Neurophysiological Photometry in 2019 focused on developing expert consensus recommendations for healthy light environments, based on the mel-EDI measurement system [127]. Brown et al. (2020) recommended a minimum mel-EDI of 250 lx at 1.2 m throughout the day, preferably using daylight and followed by blue-enriched polychromatic white light. A maximum mel-EDI of 10 lx is recommended at 1.2 m height, starting at least 3-hr before bedtime, while the maximum mel-EDI value during sleeping is 1 lx [127]. It should be noted here that the manuscript prepared by the experts is not yet peer-reviewed. In addition, no authoritative standards body approved the recommended lighting levels, including CIE and IES [124]. Table 2 summarizes the circadian lighting thresholds and metrics used by some of the well-known standards and guidelines.

Table 2. Circadian lighting thresholds and exposure times are defined in standards and guidelines.

<table>
<tr><th>Standard/Guideline</th><th>Sponsor</th><th>Metric</th><th>Circadian Lighting Target Value</th><th>Exposure Time</th></tr>
<tr><td rowspan="3">Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People
Design Guideline 24480 [128]</td><td rowspan="3">Underwriters Laboratories</td><td rowspan="3">Circadian Stimulus (CS)</td><td>CS ≥ 0.3 (EV = 448 lx) *</td><td>≥2 h per day (7:00 a.m.–4:00 p.m.)</td></tr>
<tr><td>CS ≤ 0.2</td><td>During the evening</td></tr>
<tr><td>CS ≤ 0.1</td><td>At night</td></tr>
<tr><td rowspan="5">Circadian Lighting Design [60]
2020 version</td><td rowspan="5">International Well Building Standard</td><td rowspan="5">Equivalent Melanopic Lux (EML)</td><td>Workstations ≥200 EML (daylight and electrical lighting) or, ≥150 EML (electrical lighting)</td><td>9:00 a.m.–1:00 p.m.</td></tr>
<tr><td>Living environment ≥200 EML (E_V = 321 lx) *</td><td>During the day</td></tr>
<tr><td>Living environment ≤ 50 EML</td><td>At night</td></tr>
<tr><td>Breakrooms ≥ 250 EML</td><td>Not specified</td></tr>
<tr><td>Learning areas ≥ 125 EML</td><td>4 h per day</td></tr>
<tr><td rowspan="2">DIN SPEC 67600:2013-04
Biologically effective illumination—Design guidelines [104]</td><td rowspan="2">German Institute for Standardization (DIN)</td><td rowspan="2">Photopic illuminance</td><td>≥250 lx at CCT = 8000 K or, ≥290 lx at CCT = 6500 K</td><td>Several hours during the day</td></tr>
<tr><td>≤50 lx at CCT ≤ 2700 K</td><td>In the evening</td></tr>
<tr><td rowspan="3">Recommendations for Healthy Daytime, Evening, and Night-Time Indoor Light Exposure [127]</td><td rowspan="3">Expert consensus recommandations-Brown et al. (2020)</td><td rowspan="3">mel-EDI</td><td>Mel-EDI = 250 lx</td><td>During the day</td></tr>
<tr><td>Mel-EDI = 10 lx</td><td>≥3 h before bedtime</td></tr>
<tr><td>Mel-EDI = 1 lx</td><td>During sleep</td></tr>
</table>

* Required corneal illuminance (E_V) based on the spectrum of a 4000 K fluorescent lamp typically used in offices [69].

7. Main Findings

Studies investigated the impact of different design elements on light features linked to circadian stimulation. Architectural, urban, technological, and interior design factors affect the light spectrum, intensity, spatial pattern, and temporal patterns inside spaces [41]. Designers define these factors from the early stages of design. The proper design of architectural factors and consideration of humans' lighting needs increase the efficiency of spaces. Furthermore, designers also determine the view direction of occupants and distance from windows through interior design (e.g., arranging the furniture toward windows). The proper design of these factors also plays a significant role in providing the required corneal illuminance.

Table 3 extends the work of [41] and includes the results of more recent papers investigating the effect of some architectural and interior design parameters on light characteristics perceived by space users. The studies that were conducted focused on five architectural factors and their properties: windows, shading devices, surface reflectance, space characteristics, and glazing. All properties of the investigated architectural factors affected the light level/intensity inside spaces, either positively or negatively, except the geometry of both windows and the space itself. The spectrum of architectural lighting perceived by space users is significantly determined by the color and reflectance of the architectural elements, as well as the orientation of the apertures, as daylight admitted from the eastern facades in the morning has a different spectrum than daylight admitted from eastern facades at dusk. The spatial pattern of light is related to the geometry of the space and windows, and the type of sidelighting (bilateral or unilateral). Location also plays a role in the resultant spatial pattern of light; due to the different solar angles and how that influences daylight penetration inside buildings. The temporal pattern is the least affected light factor by the architectural design since it is more user-dependent [28,57].

Table 3. Architectural factors affecting light-related factors that are essential to circadian-effective lighting.

Architectural Factor	**Property**	**Affected Light Factor**			
		Intensity	**Spectrum**	**Spatial Pattern**	**Temporal Pattern**
Windows properties	Area	√			
	Location	√		√	
	Orientation	√	√		√
	Geometry			√	
	Window head height	√		√	
Shading devices and external obstruction properties	Color	√	√		
	reflectance	√	√		
	orientation	√			√
	openness	√			
Internal surfaces and furniture properties	Color	√	√		
	reflectance	√	√		
Space properties	Geometry			√	
	Depth	√		√	
	Bilateral or unilateral sidelighting	√		√	
Glazing properties	Transmittance	√			
	Color	√	√		
	Coatings	√	√		
	Glass tinting	√	√		
	Interlayer tinting	√	√		

The role of architectural design in creating effective circadian spaces is a somewhat new topic. Although recent studies investigated the effect of some design parameters on circadian lighting, many others are not yet explored. Table 4 summarizes the design factors examined so far in terms of the circadian potential of spaces. Best practices to improve the circadian efficiency of spaces are also summarized. All these practices can be applied to new construction projects. However, very few are applicable to retrofit projects, such as changing the color and reflectance of interior surfaces, changing the glazing type, changing the luminaire type, and relocating/reordering the furniture. A general rule of circadian-effective lighting design is to increase the indirect light to provide sufficient vertical illuminance at the eye level. The architectural design of spaces should aim to admit the maximum daylight quantity, as it is more potent in stimulating the circadian system and in reducing the use of electrical lighting. Tradeoffs that are necessary to provide visual comfort should be considered here. The architectural design should also consider the activities taking place inside spaces and the users' needs for alerting or relaxing interior environments. Hence, design criteria, as with visual requirements criteria, should be created at the early stage of the architectural design process to define the intended circadian lighting design requirements.

Lighting design practices and standards are still based only on the visual performance and comfort measures. Serious changes in lighting design are required to reflect the current knowledge in the non-visual-related research on light. Human-centric lighting design is a great starting step towards upgrading lighting design and its role in supporting human comfort and needs. To date, there are no agreed-upon thresholds or exposure times for circadian-effective lighting. Authoritative standard bodies should define consensus-based standards and guidelines for circadian lighting design. Manufacturers are urged to employ new lighting technologies, such as multi-channel LEDs, in developing more circadian-effective, energy-efficient, as well as visually functional lighting fixtures. Future research should focus on developing control systems and methods for better integration between daylighting and artificial lighting to achieve both visual and non-visual lighting benefits.

Table 4. Design parameters and properties investigated for non-visual benefits.

Design Parameters	Property	References	Best Practices
Space dimensions	Room depth	[45]	Reducing room depth for better circadian potential through inter-reflections
Walls	Color	[47,48,58,59,64–67]	Painting walls with neutral colors, such as white and gray, to increase CS
	Reflectance	[3,11,12,48,55–57]	Higher surface reflectance to increase inter-reflections and CS
Windows	Area or WWR	[11,12,25,45,56]	Higher WWR for better CS
	Orientation	[45,46,55]	South, followed by east, windows are the best for circadian stimulation
	Window head height	[45]	Higher window head height results in more daylight penetration
Glazing	Color	[48,53,76]	Use neutral glazing, followed by blue-tinted glazing for better CS
	Transmittance	[48,53]	Higher transmittance for higher non-visual benefits
	Type (clear glass, single-zone electrochromic glass (EC), and three-zone EC glass)	[77]	Three-zone EC glazing balances melanopic and photopic illuminance
Shading devices	Type (horizontal blinds vs. electrochromic glazing)	[45]	Use shading devices that do not obstruct views to the sky (e.g., horizontal binds)
	Color	[62]	Blue shading panels increase intensity and distribution of melanopic luminance, compared to red
	Reflectance		Matt shading panels magnify the impact of panels' color on melanopic illuminance
	Orientation		Horizontal shading panels have more impact on melanopic and photopic illuminance than vertical panels
	Openness		Reducing openness between panels magnifies the impact of vertical shading panels on daylight non-visual effects

Table 4. *Cont.*

Design Parameters	Property	References	Best Practices
Externa lobstructions	Color	[52,58]	Light color shading obstacles have less impact on the circadian efficacy of indoor spaces
	Sky block	[25,45,55]	Design for better daylight access (no/less obstructions to the sky)
Furniture	Location of furniture (distance from window)	[41,46,55]	Closer to windows is better for circadian stimulation
	Furniture placement (view direction)	[44–46,58,77]	Best view direction is facing the window, followed by parallel to window
	Furniture reflectance	[3,11]	Higher reflectance is better
Luminaires	Luminaire type (troffers, direct linear pendant, direct/indirect linear pendant, indirect linear pendant, and recessed downlight)	[43,88]	Linear pendants and troffers with some direct components are the most efficient for circadian stimulation
	Luminaire direction (uplighting vs. downlighting)	[20,21]	Using direct–indirect lighting is better than using just direct or indirect lighting

8. Conclusions, Recommendations, and Future Work

The non-visual effects of light add new requirements to the indoor lighting environments. The role of architectural design in providing the recommended circadian metrics requirements is undeniable. Studies have shown that architectural design elements affect the visual and circadian efficiency of spaces, although the weight of each element is not yet well understood. While the visual efficiency of spaces requires a direct lighting component, indirect lighting best achieves circadian efficiency. The role of architectural design in creating circadian-effective spaces is best employed in new design projects. However, retrofit projects can adapt some architectural and interior design features to provide circadian benefits. Easy adjustments to spaces can increase the indirect component of light and boost the circadian system, such as painting surfaces with neutral colors, adding highly reflectance finishes, and adjusting the luminaires position/direction to face highly reflectance surfaces, especially the ceiling.

Daylight is the best light source to provide circadian stimulation and energy efficiency. When daylight is not present or sufficient, electrical lighting is used. Researchers are working on improving the circadian and energy efficiency of electrical lighting. Methods to create circadian-effective spaces using electrical lighting include increasing the light intensity and/or providing lights with more short-wavelength content in their spectrum. These two general methods might affect the energy consumption of lighting. Lighting manufacturers should develop new lighting products and solutions to satisfy the requirements of circadian needs without increasing energy loads. LED technology is a promising solution for improving the visual, non-visual, and energy efficiency of electrical lighting.

Future work on the role of architectural design in creating circadian-efficient spaces should include investigating other design factors that might impact increasing the direct and indirect light, such as the ceiling height and several types of shading devices. Many technologies are available today to improve the visual performance and energy efficiency of the built environment. The effect of these new technologies, such as smart glass technologies and transparent photovoltaic glazing, on providing the non-visual quality of spaces should be investigated.

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