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Photopic and Melanopic Analysis of Daylight Through Glazing in Indoor Environments

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Abstract: Daylight influences more than just our vision; elements such as its intensity and spectral composition can significantly impact our circadian rhythms and, consequently, our overall well-being. In this study, we present an analysis of a classroom simulated in Dialux, involving a comprehensive examination of natural daylight through a specific type of glazing, assessing their photopic characteristics and their influence on the human circadian system in individuals aged 32 and 70 years. Our findings highlight that spectral data from daylight (D75, D65, and D50) and glazing transmittance can be easily used to evaluate the melanopic equivalent daylight illuminance (mel-EDI) in addition to standard photopic illuminance, applying a $f\left(\frac{M}{P}\right)_{Glazing}$ factor calculated from the spectral characteristics of both daylight and glazing transmittance. Our results provide new insights for users to more effectively assess daylighting quality and its implications within indoor environments.

Keywords: daylight; circadian effects; spectral power distribution; transmittance; indoor environments

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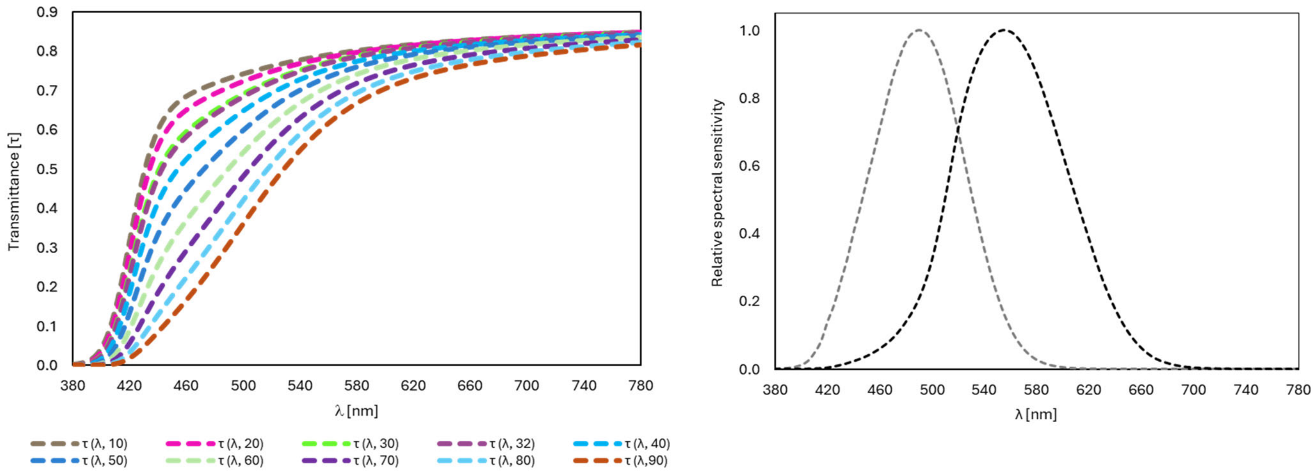
1. Introduction

Humans have primarily lived under the influence of natural light provided by the sun and the celestial vault with its varied configurations. This light is crucial for regulating circadian rhythms, which govern physiological processes such as sleep–wake cycles, hormone production, and metabolism. Several studies have already shown that adequate exposure to natural light helps maintain a healthy circadian system, positively impacting overall health and mood [1–3].

Light refers to electromagnetic radiation between wavelengths of 380 nm and 780 nm, detected by specialized cells (cones and rods) in the human retina. Cones are responsible for vision and color perception at photopic levels, while rods are responsible for scotopic vision, lacking color perception [4]. However, research conducted over the past two decades has revealed a second pathway in the eye comprising intrinsically photosensitive retinal ganglion cells (ipRGCs) [5,6], sensitive to shorter wavelengths of visible light, particularly around 480 nm, modified by the absorption spectra of the ocular media, shifted from 480 nm to 487 nm (for a 20-year-old observer) or 496 nm (for an 80-year-old observer) (Figure 1), and playing a crucial role in regulating circadian rhythms by transmitting signals to the hypothalamus through the retinohypothalamic tract [7]. Additionally, ipRGCs serve as the master clock, synchronizing the circadian rhythms in peripheral tissues and organs. Light significantly influences hormone production in various glands, including the pineal gland (melatonin production) and the pituitary gland, in conjunction with the hypothalamus [8,9]. These glands contribute to the regulation of a wide array of hormones, such as serotonin, dopamine, leptin, and ghrelin, which collectively help maintain physiological balance and overall well-being [10]. The disruption of circadian rhythms can have short-term negative effects, such as jet lag, and long-term consequences, like sleep disorders and psychiatric conditions such as seasonal affective disorder and bipolar disorder [9,10]. Additionally, with age, the number of ipRGCs decreases, altering their distribution and morphology on the retina, which results in reduced light input to rods, S-cones, and ipRGCs [11].



(**a**) (**b**)

Figure 1. (**a**): Spectral transmittance of the lens depending on age. The spectral transmittance for each decade of life, τ (λ, age), is shown, with a reference observer of 32 years of age. Reproduced from [12] (**b**): Relative spectral sensitivity of the eye, melanopic (gray) and photopic (black).

Since much of our daily activities take place indoors, proper lighting is crucial for successful task performance and individual well-being. Light from any source (natural or artificial) reaches different surfaces where observable objects reflect, transmit, or diffuse light. The levels and uniformity of illuminance on these surfaces must follow relevant regulations, optimizing energy efficiency and selecting luminaires that align with the room's category or desired overall image. Moreover, depending on the type of glazing used for windows, light with distinct characteristics inside the space is obtained, and artificial lighting is necessary in most cases to achieve optimal lighting conditions, both for visual and non-visual purposes. However, the latest indoor lighting standards, such as UNE-EN 12464-1 [13], emphasize visual effects (illuminance, uniformity on work surfaces, and glare), and the non-image forming (NIF) results in feasible lighting projects. Just as horizontal illuminance and uniformity are crucial for visual effects, determining vertical illuminance on the eye's corneal plane at specific heights (120 cm in work areas and 170 cm in passageways) is important for non-visual effects. These values can be adjusted by designers based on activities and user height. The optical pathway responds instantly to light, while the NIF pathway has a slower, cumulative response influenced by the light's spectrum, intensity, exposure duration, and spatial pattern [2]. Additionally, the CIE S 026/E:2018 standard [14] includes information on the visual field, noting that light exposure on the lower part of the retina more effectively suppresses melatonin compared to the upper part and that light on the nasal side is biologically more potent than on the temporal side [11].

Although it is not mandatory, it seems important to consider natural daylight from the outdoors in these issues since it provides good melanopic/photopic ratios for activating the circadian system [15–17]. Daylight quality and quantity in indoor environments are influenced by building envelope characteristics, glazing types, and wall colors, making it essential to analyze its characteristics in indoor spaces [15,18–20]. The described criteria are crucial because facing a bright window versus a poorly illuminated wall inside a building makes a significant difference. Previous lighting standards focused only on task locations and the horizontal plane, but advancements in understanding NIF of light now emphasize the importance of light reaching the vertical plane, specifically the user's retinal plane. To quantify the biological influence of a light stimulus, different quantities are utilized, such as the melanopic equivalent daylight illuminance (mel-EDI) from CIE S 026 [14] and equivalent melanopic lux (EML) from the WELL Building Standard v2 [21]. As it was described in a previous work, basic expressions used in lighting projects that consider both photopic and melanopic actions can be calculated with the Melanopic Action Factor parameter (MAF) [22] by EML = 1.218 × MAF × E_photopic from photopic illuminance and mel-EDI = 1.104 × MAF × E_photopic; moreover, CIE S 026 [14] and WELL Building Standard v2 [21] are related: by combining both of them, EML = 1.104 × mel-EDI.

When studying the NIF effects of light, it is essential to understand both the illumination present and the illumination perceived by individuals. This is important because the human eye's crystalline lens undergoes changes with age, significantly reducing transmittance for shorter wavelengths [12,23]. Figure 1a displays the different transmittance curves over the years. The spectral correction factor for age-related lens transmission, $k(\lambda,Y) = (\tau(\lambda,Y))/(\tau(\lambda,32))$, must be considered when studying the NIF effects of light [12]. This factor, defined as 1 for age 32 and decreasing with age, estimates the actual light transmission through the pupil to the retina, allowing for personalized calculation of circadian light reaching the retinal plane for each age [23].

This paper presents a method for calculating melanopic light based on photopic illuminance, focusing on defining an intrinsic parameter specific to the glazing material used in indoor lighting projects, $f\left(\frac{M}{P}\right)_{Glazing}$, which can predict its melanopic efficiency. This method is analyzed under three different outdoor daylight conditions and serves as a case study for evaluating the influence of the spectral characteristics of window glazing, the type of light entering through the windows, the orientation of the windows, the position of the observer within the space, and the age of the occupants.

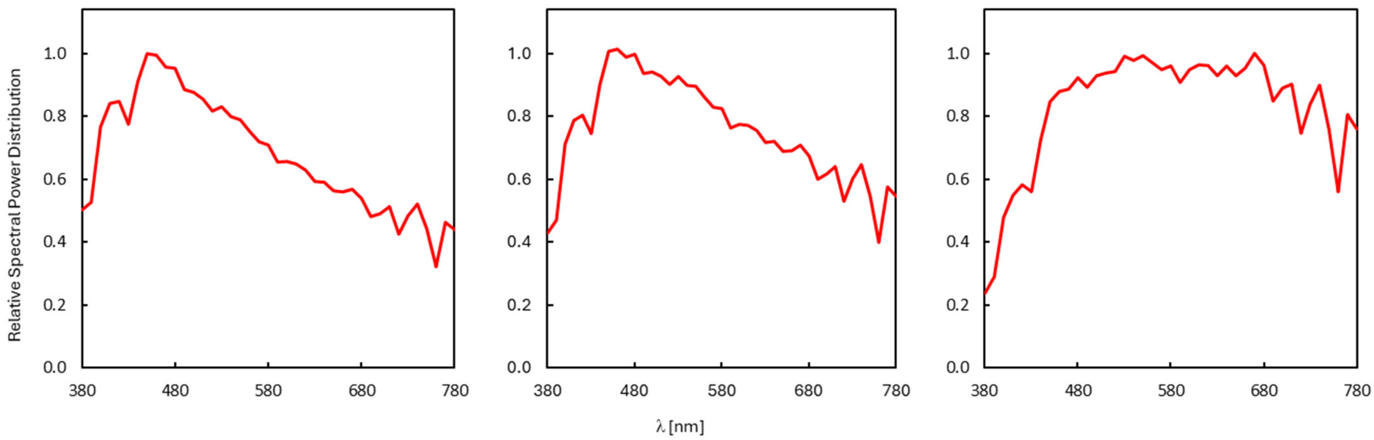
2. Materials and Methods

2.1. Daylight

Three different sky conditions were considered to simplify the proposed analysis: overcast, equivalent to a correlated color temperature (CCT) of D75 (7500 K) representing cool daylight; medium of D65 (6500 K), reflecting standard daylight; and clear of D50 (5000 K), simulating warmer, diffused daylight (Figure 2). This study also considered other variables such as orientation and date of the year. Specifically, four orientations of the windows were studied, facing north, south, east, and west. For each orientation, four possible dates were examined, each corresponding to the beginning of a season (equinox—spring start; solstice—summer start; equinox—autumn start; solstice–winter start), with calculations performed at a fixed time of 11:00 a.m. (GTM + 1) along the evaluated period.

2.2. Photopic Lighting Calculations

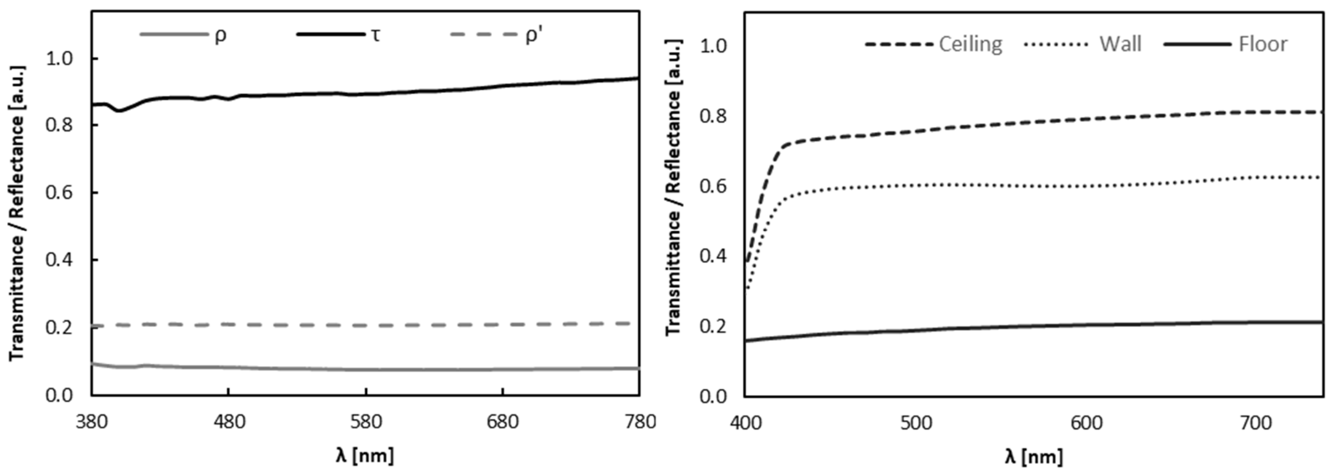
The software used for the design of the classroom and photopic lighting calculations was DiaLux Evo 12.0. (DIAL GmbH, Lüdenscheid, Germany). This program allows for simulations of lighting in different indoor spaces under various outdoor conditions. In this case, a classroom located at the University of Zaragoza (position: coordinates −0.9° longitude, 41.64° latitude) was simulated (dimensions: 8.8 m length, 6.7 m width, 2.8 m height). Lighting: three windows, each measuring 1.8 m in length and 1.2 m in width, equidistantly located on one sidewall and no artificial lighting, with transmittance of 90% (Figure 3a). To ensure the model closely resembled real conditions, we collected reflectance data using a calibrated CM-700d spectrophotometer (Konica Minolta Sensing Inc., Osaka, Japan), which has a 2% uncertainty in reflectance measurements from 400 nm to 740 nm. This device measures the reflectance of materials by positioning the colorimeter sensor near the surface and recording the reading. These data were then used to simulate furniture with distinct colors and textures (furniture: 15 tables and 30 chairs arranged in five rows, teacher's desk and chair, blackboard), as well as reflection degrees for the walls (60%), ceiling (80%), and floor (20%), as shown in Figure 3b. This ensures that the simulation accurately represents the real environment.



(**a**) (**b**) (**c**)

Daylight	CCT (K)	x	y	CRI
D75	7506	0.2991	0.3149	99.8
D65	6503	0.3127	0.3291	99.8
D50	5002	0.3457	0.3585	99.8

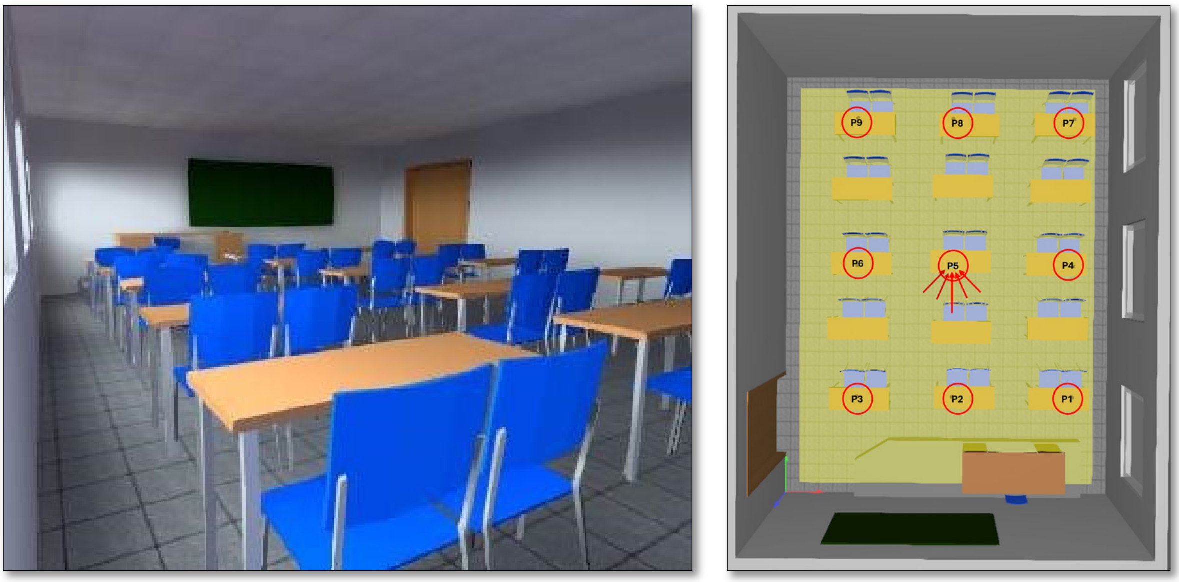
Figure 2. (**a**) Relative SPD (spectral power distribution) of the D75 daylight. (**b**) Relative SPD of the D65 daylight. (**c**) Relative SPD of the D50 daylight. Down: characteristics of standard daylight according to CIE 1931—chromatic coordinates (x, y), correlated color temperature (CCT) measured in Kelvin (K), and color rendering index (CRI).



(**a**) (**b**)

Figure 3. (**a**) Spectral transmittance (τ) and front (ρ) and rear (ρ′) reflectance in the visible range. Glazing is "low iron 6 mm SS90". (**b**) Spectral reflectance of walls, ceiling, and floor. Transmittance/reflectance is measured in arbitrary units (a.u.), and wavelength is measured in nanometers (nm).

To study the lighting inside the classroom (Figure 4a), a workplane 0.8 m over the floor and nine calculation points were placed evenly throughout the space at a height of 1.2 m, corresponding to the standard eye level of a seated person. For each point, the photopic illuminance value on the vertical plane (corneal plane) was measured in five different viewing directions: 0° (forward view), ±30°, and ±45°, as shown in Figure 4b.



(**a**) (**b**)

Figure 4. (**a**) Classroom simulated in Dialux used to perform the analysis of the daylight indoors. (**b**) Overview of the studied classroom points and angles of evaluation (0° (forward view), ±30°, and ±45°, simulated in P5). Points P1 to P9 represent the nine locations where measurements were conducted within the classroom.

First, the results obtained were calculated for each of the evaluated points (P1 to P9) within the room. The average illuminance reaching the corneal plane was calculated based on the viewing direction, with 50% weight given to the angle of 0°, 15% to the angles ±30°, and 10% to the directions ±45°. This accounts for the dynamic nature of the eye and the variation in the corneal plane in these studied directions. To simplify the calculation, an average of the illumination at each point throughout the year was determined by averaging the values obtained for the two solstices and the two equinoxes.

2.3. Theoretical Circadian Considerations in Lighting for Glazing

In this section, we introduce a novel methodology used for assessing the potential circadian effect of a glazing through the calculation of a factor derived from the ratio of melanopic to photopic illuminance, denoted as $f\left(\frac{M}{P}\right)_{Glazing}$. This factor is based on the spectral characteristics of both daylight and glazing materials, which allows for a more predictive analysis of circadian lighting indoor conditions. Unlike previous studies that focus solely on light sources, our approach incorporates the impact of glazing transmittance, by applying this factor, we offer a practical means to evaluate both photopic and melanopic effects in a variety of outdoor environments, which is particularly useful in scenarios where daylight plays a major role. The method we propose is derived from the conventional relationship between radiometric and photometric magnitudes and the current standards previously outlined by Sanchez et al. [22]. The equivalent daylight illuminance (mel-EDI or EDI) is defined by the CIE S 026 standard [14], and normalization is proposed with the melanopic illuminance provided by the standard illuminant D65 (daylight CCT = 6500 K). A light-source type D65 furnishing photopic illuminance $E_{photopic,D65}$ (E) to provide the same melanopic illuminance $E_{melanopic,D65}$ (EDI) can be calculated as $EDI = 1.104 \times MAF \times E$, with

$$MAF = \frac{\int_{\lambda=380}^{780} SPD(\lambda) S_{mel}(\lambda) d\lambda}{\int_{\lambda=380}^{780} SPD(\lambda) V(\lambda) d\lambda}$$

The glazing-dependent spectral correction factor for glazing spectral transmission $\tau(\lambda)$ is a parameter that must be considered to address the non-visual effects of light in lighting designs where the window material plays a crucial role. This value, in photometry, is defined as

$$\tau = \frac{\int_{\lambda=380}^{780} SPD(\lambda)\tau(\lambda)V(\lambda)d\lambda}{\int_{\lambda=380}^{780} SPD(\lambda)V(\lambda)d\lambda}$$

And the equivalent in circadian lighting should be

$$\tau_{mel} = \frac{\int_{\lambda=380}^{780} SPD(\lambda)\tau(\lambda)S_{mel}(\lambda)d\lambda}{\int_{\lambda=380}^{780} SPD(\lambda)S_{mel}(\lambda)d\lambda}$$

As described below, equations used to compute circadian EDI level after glazing $\left(EDI_{Post-glazing}\right)$ are related to the EDI level before glazing $\left(EDI_{Pre-glazing}\right)$ thorough the equation $EDI_{Post-glazing} = \tau_{mel} EDI_{Pre-glazing}$; now, they must be modified to determine a new parameter, intrinsic to the glazing, $MAF_{Glazing}$, to easily predict the circadian level of light in case this material is used:

$$EDI_{Post-glazing} = \tau_{mel}\ EDI_{Pre-glazing} = 1.104\ \tau_{mel}\ MAF\ E =$$

$$1.104\ \frac{\int_{\lambda=380}^{780} SPD(\lambda)\ \tau(\lambda)\ S_{mel}(\lambda)\ d\lambda}{\int_{\lambda=380}^{780} SPD(\lambda)\ S_{mel}(\lambda)\ d\lambda}\ \frac{\int_{\lambda=380}^{780} SPD(\lambda)\ S_{mel}(\lambda)\ d\lambda}{\int_{\lambda=380}^{780} SPD(\lambda)\ V(\lambda)\ d\lambda}\ E =$$

$$1.104\ \frac{\int_{\lambda=380}^{780} SPD(\lambda)\ \tau(\lambda)\ S_{mel}(\lambda)\ d\lambda}{\int_{\lambda=380}^{780} SPD(\lambda)\ V(\lambda)\ d\lambda}\ E =$$

$$1.104\ \frac{\int_{\lambda=380}^{780} SPD(\lambda)\ \tau(\lambda)\ S_{mel}(\lambda)\ d\lambda}{\int_{\lambda=380}^{780} SPD(\lambda)\ \tau(\lambda)\ V(\lambda)\ d\lambda}\ \frac{\int_{\lambda=380}^{780} SPD(\lambda)\ \tau(\lambda)\ V(\lambda)\ d\lambda}{\int_{\lambda=380}^{780} SPD(\lambda)\ V(\lambda)\ d\lambda}\ E =$$

$$1.104\ \tau\ \ MAF_{Glazing}\ E = 1.104\ MAF_{Glazing} E_{Post-glazing}$$

$$MAF_{Glazing} = \frac{\int_{\lambda=380}^{780} SPD(\lambda)\ \tau(\lambda)\ S_{mel}(\lambda)\ d\lambda}{\int_{\lambda=380}^{780} SPD(\lambda)\ \tau(\lambda)\ V(\lambda)\ d\lambda}$$

$$f\left(\frac{M}{P}\right)_{Glazing} = 1.104\ MAF_{Glazing} = 1.104\ \frac{\int_{\lambda=380}^{780} SPD(\lambda)\ \tau(\lambda)\ S_{mel}(\lambda)\ d\lambda}{\int_{\lambda=380}^{780} SPD(\lambda)\ \tau(\lambda)\ V(\lambda)\ d\lambda}$$

$MAF_{Glazing}$ is a new parameter that can be straightforwardly calculated from the SPD of any light and for any spectral transmittance of the glazing by an easy expression, similar to the expression defined for the light. It should be used, as description shows, to effectively predict the illumination levels in a point from general levels of E without glazing, knowing the absolute transmittance of the material, or with $E_{Post-glazing}$ when the window is considered. It leads to predict the amount of light reaching a point to be compared with different daylight spectral and glazing transmittance. The $f\left(\frac{M}{P}\right)_{Glazing}$ melanopic/photopic correction factor is defined. It can be useful in determining the best material of the windows depending on the SPD of the skydome to accomplish the requirements stablished by the standards in different hospital areas, offices, schools, or residential homes.

As an application example, consider glazing with a transmittance $\tau \sim 0.90$ (depending on the SPD of the daylight), for a requirement of $E_{Post-glazing} \sim 250$ lx, an outdoor illuminance $E \sim 279$ lx is needed. Table 1 shows circadian light depending on the SPD of the skydome through the glazing. For this specific glass, Figure 5 displays the different $MAF_{Glazing}$. If the same material is used with a different transmittance, for example $\tau \sim 0.60$, $MAF_{Glazing}$ remains constant, intrinsic to the glazing type, with differences only in both photopic and melanopic illuminance. With the same requirement of $E_{Post-glazing} \sim 250$ lx, an outdoor level of E ~ 419 lx is needed, and $EDI_{Post-glazing}$ is 266, 247, and 210 for 7500 K, 6500 K, and 5000 K, respectively. Figure 5 shows the tendency of the curve of $MAF_{Glazing}$ when other daylight CCT needs to be considered. It could be extensible to other daylight spectra and glazing since both of them used to be flat in the spectral range evaluated, 380–780 nm. The $f\left(\frac{M}{P}\right)_{Glazing}$ parameter can be calculated by multiplying this factor by 1.104, as previously described.

Table 1. Circadian light depending on the spectral power distribution (SPD) of the skydome through the glazing. Dxx (K): daylight correlated color temperature (K), MAF_{Dxx}: Melanopic Action Factor of daylight, τ: transmittance of glazing, $MAF_{Glazing}$: Melanopic Action Factor of glazing, $EDI_{Post-glazing}$: equivalent daylight illuminance after glazing, $f\left(\frac{M}{P}\right)_{Glazing}$: ratio of melanopic to photopic illuminance.

Dxx (K)	MAF_{Dxx}	τ	$MAF_{Glazing}$	$EDI_{Post-glazing}$	$f(\frac{M}{P})_{Glazing}$
8000	1.004	0.8945	0.995	274	1.098
7500	0.975	0.8945	0.966	266	1.066
7000	0.942	0.8946	0.934	257	1.031
6500	0.906	0.8947	0.898	247	0.991
6000	0.865	0.8948	0.858	236	0.947
5500	0.819	0.8949	0.812	224	0.896
5000	0.767	0.8951	0.761	210	0.840

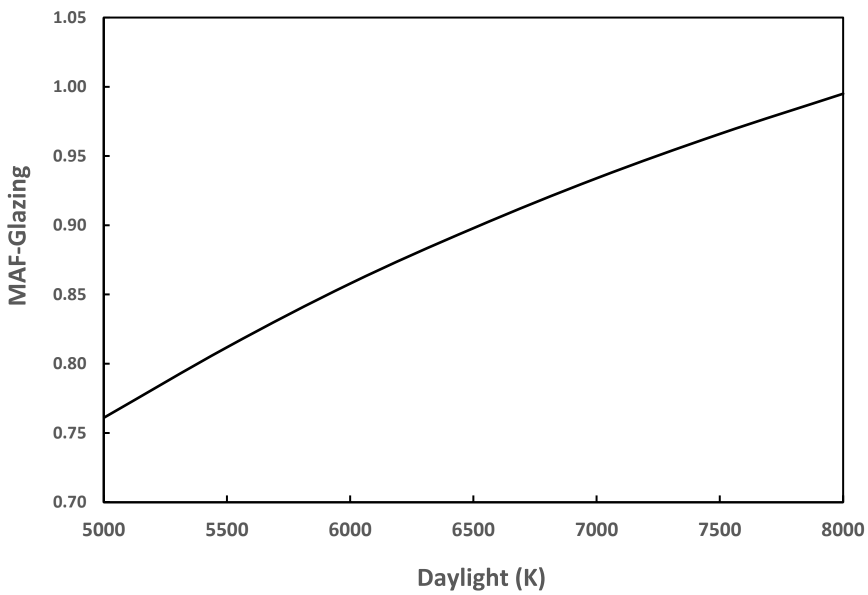


Figure 5. The tendency of the Melanopic Action Factor of glazing ($MAF_{Glazing}$) curve considering daylight correlated color temperature (CCT) from 5000 K to 8000 K.

2.4. Aging Melanopic Lighting Calculation

Finally, a custom calculation tool was developed based on the one developed by Houser et al. [24] and described in the ANSI/IES TM-30-20 Advanced Calculation Tool v2.04 [25]. This tool allows for the inclusion of the spectral transmittance of diverse types of glazing and the selection of the daylight type for the calculation. With this tool, it is possible to determine the values of the mel-EDI and EML factors based on user-defined photopic illuminance. In this case, these values were calculated using Dialux Evo 12.0 software, as mentioned in the previous section. Additionally, the original tool was modified for this study to account for variations when considering a standard observer of 32 years (typical reference) or 70 years of age. These calculations consider the transmittance values of the lens and its dependence on age to calculate the melanopic light that potentially reaches the retina, as plotted in Figure 1.

3. Results and Discussion

The results obtained for photopic lighting at the corneal plane based on the selection of all the previously described study parameters are presented in Figure 6 according to the orientation and daylight evaluated.

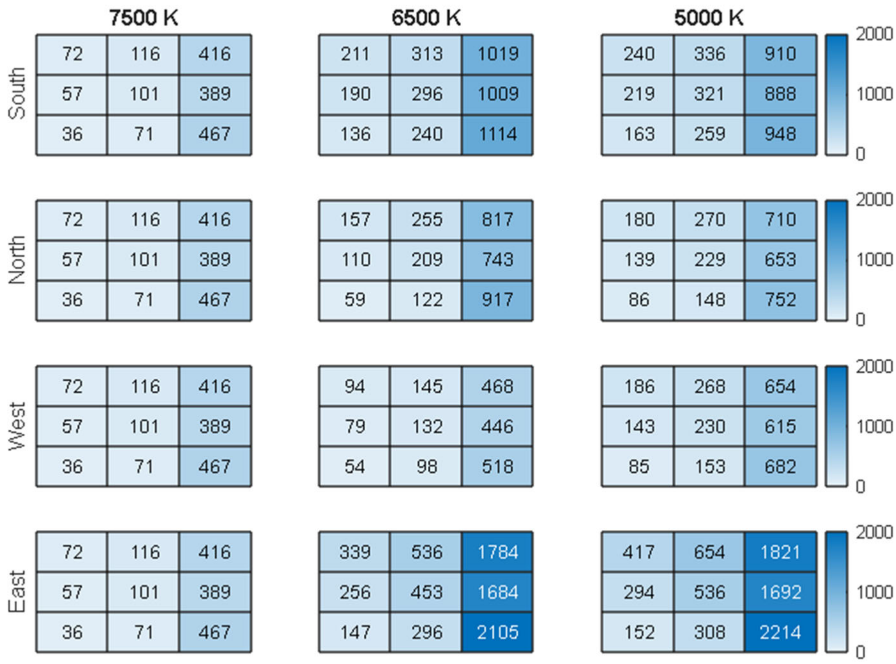


Figure 6. Illuminance level (lx) at the corneal plane in the nine points inside the room, by orientation and daylight.

The quality and intensity of daylight reaching the corneal plane of a person inside a building are influenced by several factors, including the orientation of the space, the type of sky (clear, overcast, etc.), the season, and the transmittance of the window materials. As Figure 6 shows, daylight availability and its spectral composition are responsible for significant variations in the orientation of the windows of a building. Specifically, for clear and medium sky, the east orientation exhibits significantly higher illuminance levels compared to other orientations. In contrast, spaces with north/west-facing windows generally receive lower illuminance levels in the morning due to the absence of direct sunlight. Notably, the different orientations present relatively consistent variations throughout the year since the plotted values are the mean of the four evaluated days in different seasons, with fluctuations of approximately 30–40%, signifying its relatively stable performance in transmitting daylight across the year. These variations have been previously described, suggesting that adaptive lighting configurations, considering natural and artificial indoor combinations, are the best choice in lighting projects. Regulating indoor lighting by controlling natural light through windows significantly reduces energy consumption by dynamically adjusting artificial lighting levels. This approach could save between 21% and 80% of energy in summer and up to 60% in winter compared to static setups, ensuring optimal illumination and improving visual comfort and overall well-being [16]. Seasonal changes significantly affect the amount and quality of daylight entering indoor spaces. For instance, the angle of the sun's path changes throughout the year, affecting the intensity and duration of sunlight received on different façades. East-facing windows, which capture morning sunlight, tend to show less variation in daylight availability across seasons compared to south-facing windows, which receive more intense sunlight during summer months.

Moreover, the type of glazing material and its properties, such as transmittance and spectral filtering, play a pivotal role in determining the quality of light that penetrates indoors. In lighting project design, regardless of its purpose, it is imperative to pre-emptively understand the material properties to select the most suitable options. We present a method for easily calculating potential circadian light using a few parameters commonly employed in determining colorimetric properties, typically supplied by manufacturers. It could be useful to know the behaviors of the glazing in addition to others that have been described in smart glazing, with specific affections on hue and chroma, with potential problems for completing tasks requiring accurate color perception, but with a positive shift toward yellow for a more joyful atmosphere [26]. It has been described that the glazing color and transmittance affect alertness, mood, and performance in daylit workspaces, with higher circadian light levels mitigating negative impacts. Higher visual transmittance and neutral color improve mood and are preferable for visual performance; blue glazing is also preferable for visual performance, whereas bronze glazing may impair working performance, though no clear divergences in nonvisual performance are found between various colored and neutral glazing systems [27]. Meanwhile, a spectral lighting simulation has been used to calculate non-visual metrics and evaluate the surface color appearance for clear and electrochromic glazing under various sky conditions, revealing that smart glazing, especially in its maximum coloration state, may negatively impact non-visual effects, necessitating well-designed artificial lighting in dense urban areas or during winter [26]. With different, and even with opposite results, in general, high-transmittance glazing allows more natural light to enter, enhancing visual comfort and circadian entrainment [28], and in contrast, glazing with lower transmittance or specific coatings can filter out certain wavelengths, reducing the overall daylight intensity but potentially altering the spectral composition to suit specific needs. The literature shows how the light combined with environments with the specific spectral characteristics of the indoor surfaces can significantly impact the final observer [29].

Our proposed method could help to analyze the glazing behavior in terms of circadian lighting since daylight illuminance from different glazing types and times of day significantly affects visual performance, alertness, physical well-being, and relaxation, with higher CCT glazing improving physical comfort and reaction time when proper illuminance is achieved [15,27]. Daylight, particularly when aligned with natural circadian rhythms, plays a crucial role in regulating the body's internal clock, influencing sleep-wake cycles, mood, and overall health [30]. The spectral quality and intensity of daylight vary throughout the day, with morning light rich in blue wavelengths being particularly effective in synchronizing the circadian system. This synchronization is vital for maintaining regular sleep patterns and hormonal balance, thereby enhancing cognitive performance and emotional well-being [31]. As such, the design and orientation of buildings should maximize exposure to natural light, especially in the morning, to support these biological processes. The type of sky also plays a crucial role; our overcast sky D75 (7500 K) shows no differences among orientations, but both medium D65 (6500 K) and clear D50 (5000 K) sky showed the highest levels with the east orientation (due to the position of the sun in the skydome at 11.00 h, the selected time for evaluating data). Throughout the year, a similar variation is observed in circadian metrics for the orientations, with changes of approximately 30–40% aligned with the photopic levels found. The results highlight discernible fluctuations linked to orientation, showcasing higher intensities adjacent to east-facing windows and lower values generally prevalent on the northern/western side. This observation underscores a consistent trend across diverse skydome types, elucidating the influential role of window direction in modulating the influx of daylight and consequent effects on the circadian system. The recurrent pattern across outdoor light conditions emphasizes how the orientation of windows significantly shapes the quantity of incoming daylight, thereby delineating its pivotal role in determining the resultant circadian impacts within indoor spaces.

Not only is the level of circadian light reaching the corneal plane of the ages important, but more interesting is the light reaching the retina of the observer. As people age, changes in circadian rhythms are significantly influenced by alterations in the ocular crystalline lens. The results obtained provide crucial insights into the diverse lighting characteristics of these materials under different daylights and orientations and demonstrate higher EDI values across all illuminants, with the east-facing orientation consistently yielding the maximum illumination. In this part, the results of the circadian lighting analysis in the EDI metric are presented, first for a standard observer of 32 years and then for an observer of 70 years (Figure 7).

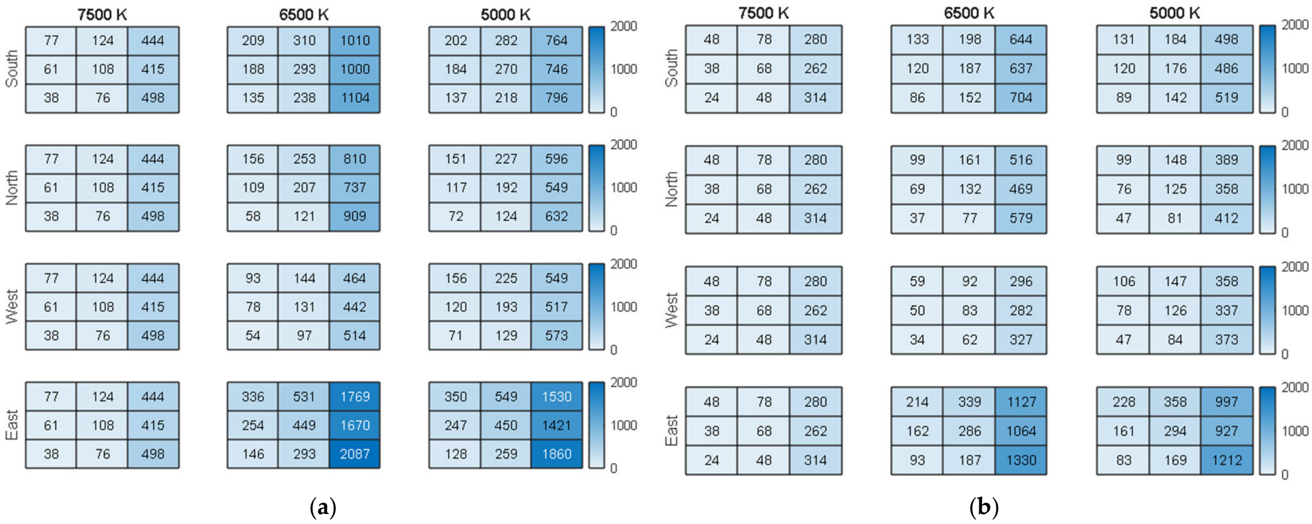


Figure 7. EDI level (mel-EDI) reaching the retina of a person located in the nine points inside the room, by orientation and by daylight: (**a**) 32-year-old individual (**b**) 70-year-old person.

The evaluated points showed significant variations in levels, with higher values observed near the windows. These variations depend on the window orientation, outdoor lighting conditions, and glazing transmittance, which have implications for circadian lighting [32,33]. Understanding how to measure specific parameters and their minimum thresholds for daily variation levels is crucial, as is providing recommendations for future buildings and lighting standards concerning melanopic EDI values. Daylight, having one of the highest potentials to induce non-visual effects, requires orientation-dependent analysis due to its varying spectral properties and colorimetric characteristics. Different regions of the sky can exhibit significant variation; for instance, skylight from a clear north sky can have a CCT ranging from 5000 to 100,000 K, influenced by factors such as orientation, seasonality, and sky conditions [34–36]. Overall, the lighting analysis conducted reveals significant variations in illuminance within the room, both in terms of the viewing direction and throughout the year [18]. Despite this observed reduction in Figure 7, both age groups show a parallel and consistent seasonal trend in lighting variation throughout the year, indicating that seasonal changes consistently affect perceived lighting values regardless of age. Additionally, the age-dependent circadian illuminance values vary based on window orientation and the evaluated outdoor daylight, emphasizing the importance of considering occupant age in lighting assessments [12]. Classrooms are used by individuals across a wide range of ages, including teachers, researchers, staff, and university students. Our study examines how light reaches the corneal plane and, subsequently, how the retina is affected by the aging of the crystalline lens, acknowledging that different users may have distinct needs and responses. By examining these effects across different ages, we ensure that our findings are relevant for all individuals in the classroom, enhancing the overall effectiveness of lighting design in educational settings.

The aging lens becomes more opaque and more yellowed, reducing its ability to transmit light, particularly shorter wavelengths such as blue light, which is crucial for circadian regulation [37,38]. This change can lead to reduced exposure to the appropriate light needed for synchronizing the biological clock, resulting in disruptions to sleep–wake patterns and hormonal regulation [31]. Furthermore, studies have shown significant individual variations in circadian photosensitivity, such as melatonin suppression, due to artificial light exposure [31]. Recommendations for appropriate light exposure often fail to account for these individual differences. For example, children who have larger pupils and a higher spectral transmittance of the crystalline lens at short wavelengths exhibit greater melatonin suppression in response to light compared to adults. Non-visual photoreception in children around the age of 10 is approximately twice that of 45-year-old adults [30]. Healthy aging is associated with a progressive decline in light transmission, and the development of cataracts exacerbates this decline, further disrupting circadian rhythms. However, cataract patients undergoing intraocular lens replacement with lenses optimized for spectral transmission can experience improvements in circadian photosensitivity, sleep quality, and cognitive function despite the smaller pupil size associated with aging [30,31,37,38]. A previous study [23] highlights key findings on the impact of lens aging on melanopsin spectral sensitivity in ipRGC and presents a simplified method to calculate melanopic contributions by age, which is crucial for personalized lighting design. Therefore, it is essential to consider these factors when designing lighting environments, especially for children and older populations, to ensure sufficient exposure to effective circadian lighting.

This study also highlights the importance of considering age-related variations in circadian responses when designing lighting for indoor environments. As individuals age, their sensitivity to light, particularly to the blue spectrum associated with circadian regulation, decreases. By incorporating age as a variable in the calculation of mel-EDI, our method offers a more tailored approach to lighting design. This enables the creation of lighting environments that are optimized not only for visual tasks but also for supporting the circadian health of occupants of different age groups. The practical tool developed through this research can be applied in educational, residential, and commercial spaces, allowing for the evaluation and adjustment of light quality to enhance well-being and productivity across a range of occupants. These results highlight the importance of selecting glazing with appropriate spectral transmittance based on outdoor conditions to enhance natural lighting in indoor environments and promote occupant well-being. Optimizing natural light and supplementing it with artificial lighting when necessary is crucial. Indoor lighting projects can benefit from integrating natural light into various areas to maximize its advantages, complemented by suitable electric lighting to conserve energy and create healthy environments. This approach should include both static lighting and the potential use of dynamic electric light to ensure visual comfort [39].

The present study introduces a novel method to calculate mel-EDI using a factor derived from the ratio of melanopic to photopic illuminance based on the spectral characteristics of daylight and glazing, $f\left(\frac{M}{P}\right)_{Glazing}$. This approach simplifies the assessment of circadian lighting conditions by integrating both visual and non-visual effects, enabling the calculation of a melanopic factor for each material and light source in the same manner as is typically performed for the light source alone. Analyzed under various daylight conditions, orientations, and occupant ages, this method provides a practical tool for optimizing indoor environments, particularly in educational settings, to enhance both visual comfort and circadian regulation for well-being.

Limitations in this study are the same as described by others [20], since CCT assigned to the three different skies is limited by simulation software (Dialux Evo 12.0), and the assignment performed in this study is based on previous experimental measurements. Digital tools have significantly advanced building behavior prediction and decision making in daylighting studies, promoting sustainable building design, though inherent uncertainties in simulation can impact result accuracy, observing discrepancies between simulated and actual daylighting performance underscoring the need for validation and applied simulation cases [40]. Specifically, one major constraint in this study is the assumption that all variables, such as material properties and light sources, behave as they would in real-world conditions. Factors such as weather variability, material aging, and occupant behavior can cause deviations from the simulated results. Nevertheless, Dialux is a widely validated tool in the lighting industry, and we followed standard guidelines, including those from the CIE, to ensure the reliability of the model. Despite these limitations, the findings offer valuable insights into photopic and melanopic illuminance in classrooms, providing a robust framework for assessing the effects of glazing on lighting conditions across different age groups.

4. Conclusions

In conclusion, our method is based on calculations from established standards and recommendations for circadian light, but we take it a step further by introducing a new parameter specifically for glazing, $f\left(\frac{M}{P}\right)_{Glazing}$. This novel approach simplifies the assessment of circadian lighting by utilizing accessible photopic measurements, providing a more comprehensive understanding of how glazing materials influence circadian regulation. The practical advantage of our method lies in its ability to efficiently optimize indoor lighting environments by considering the circadian effects of both daylight and the spectral transmittance of façade glazing materials. This shows that absolute photopic light levels are influenced by position indoors, orientations of the façade, time, and transmittance of glazing, with values rapidly modifying due to daylight factors. The findings underscore the importance of designing spaces with optimal orientations, dimensions, and appropriate glazing that can be combined with the careful selection or design of luminaires and light sources to achieve desired lighting outcomes. Additionally, this approach allows for the optimization of circadian lighting projects based on the age of the occupants. Our study provides a practical tool that can be applied in indoor environments, enabling a more effective evaluation of light quality and its impact on human well-being.

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