buildings

Article

Efficient Daylighting: The Importance of Glazing Transmittance and Room Surface Reflectance

Isabel Escobar [1], Elvira Orduna-Hospital [1,2], Justiniano Aporta [1,2] and Ana Sanchez-Cano [1,2,*]

[1] Department of Applied Physics, University of Zaragoza, 50009 Zaragoza, Spain; 775242@unizar.es (I.E.); eordunahospital@unizar.es (E.O.-H.); aporta@unizar.es (J.A.)
[2] Aragon Institute for Health Research (IIS Aragon), 50009 Zaragoza, Spain
* Correspondence: anaisa@unizar.es

Abstract: This study quantitatively analyzes the influence of the spectral characteristics, reflectance or transmittance, of different materials on the lighting of an interior space with natural and artificial light. For this purpose, a three-dimensional simulated classroom is used, where each of the components is assigned specific materials with an associated reflectance or transmittance. Additionally, two types of lighting are available: 6500 K daylight and light from six continuous spectrum LED luminaires. The lighting is evaluated on two planes: the work plane and the corneal plane (80 cm and 120 cm from the floor, respectively). Three versions of the same classroom were analyzed by varying the walls (white, blue, and red), each with a different neutral-colored floor. Furthermore, calculations were performed in each situation considering two different types of glazing in the windows, with 20% and 88% transmittance. The photopic and melanopic lighting analysis was carried out with the ALFA calculation program to verify the necessary requirements for adequate lighting. The results show that the white classroom is the best lit, followed by the blue and finally the red, due to the reflectance characteristics of the walls and floor although slight differences among them are found. It was found that in some cases, additional auxiliary luminaires would be required for proper lighting depending on the transmittance of the glazing. This study highlights the critical role of material selection in optimizing both photopic and melanopic lighting, with practical implications for energy efficiency and occupant well-being in educational spaces.

Keywords: circadian lighting; glazing transmittance; natural light; spectral reflectance

check for updates

Citation: Escobar, I.; Orduna-Hospital, E.; Aporta, J.; Sanchez-Cano, A. Efficient Daylighting: The Importance of Glazing Transmittance and Room Surface Reflectance. *Buildings* **2024**, *14*, 3108. https://doi.org/10.3390/buildings14103108

Academic Editors: Dorukalp Durmus, Wenye Hu and Lambros T. Doulos

Received: 31 July 2024
Revised: 24 September 2024
Accepted: 24 September 2024
Published: 27 September 2024

1. Introduction

With advancements in lighting technology and a growing emphasis on human comfort, modern societies design spaces for various activities, each requiring specific luminous characteristics to optimize working conditions. Natural light, a key element in these designs, has played a crucial role throughout human evolution in synchronizing circadian rhythms and modulating physiological processes long before the advent of artificial lighting [1,2]. These regulations attempt to synchronize the light we receive throughout the day with the biological clock that regulates a wide range of functions in the human body [3–6]. The light processed by our brain falls within the visible spectrum range of 380 nm to 780 nm, but the eye does not detect all visible wavelengths with the same efficiency [7]. Specifically, the eye follows the photopic curve $V(\lambda)$, which peaks at 555 nm [8]. Understanding this curve is essential for designing lighting that aligns with both visual and non-visual needs. Light enters the human eye, refracts in the cornea, passes through the crystalline lens, and is detected in the retina, which is considered an extension of the brain and where phototransduction occurs [9], this process is carried out by the photoreceptors: rods and cones [10]. Rods are highly sensitive to light but have low spatial resolution, whereas cones provide high spatial resolution but are much less sensitive to light. Cones also enable color differentiation due to the presence of three types, each more sensitive to different wavelengths: blue, green, and red [8]. These sensitive cells are the primary elements in the creation of images in the brain, but other light-sensitive cells in the eye, intrinsically photosensitive retinal ganglion cells (ipRGCs), are present [10,11]. These cells play a crucial role in non-image-forming processes; ipRGCs are primarily, but not exclusively, involved in regulating circadian rhythms [12]. These cells respond with greater sensitivity to visible light around 490 nm, following the response curve to electromagnetic radiation for melanopsin stimulation Smel(λ), in the short wavelength range, and send neural signals to the hypothalamus via the retinohypothalamic tract with various physiological purposes [12–15].

As most daily activities occur indoors, ensuring proper lighting is essential for effective task performance and overall well-being. Consequently, regulatory standards now dictate the required indoor illuminance based on activity type, the two most well-known are the International Commission on Illumination (CIE) [16–18], and the American Illuminating Engineering Society Standards (IES) [19]. Additionally, other organizations such as the International WELL Building Institute [20] promote the creation of spaces centered on people's well-being. The latest standards for indoor lighting, UNE-EN ISO 12464-1 [21], prioritize visual effects such as illuminance, uniformity on work surfaces, and glare underscoring the importance of non-visual effects in achieving effective lighting designs. For instance, while horizontal illuminance and uniformity are critical for visual effects on the work plane (WP) at 80 cm, vertical illuminance on the corneal (or view) plane (VP) of the eye at specific heights (120 cm in work areas and 170 cm in passageways) is crucial for non-visual effects. The optical pathway responds immediately to light, whereas the non-image-forming pathway shows a slower, cumulative response that is influenced by factors like light spectrum, intensity, exposure duration, and spatial pattern [5]. Additionally, the CIE S 026/E:2018 standard [16] provides insights into the visual field, indicating that light exposure to the lower part of the retina is more effective at suppressing melatonin than exposure to the upper part. It also notes that light exposure on the nasal side of the retina has a greater biological impact compared to the temporal side [22].

In indoor environments, natural daylight is crucial as it provides beneficial melanopic/photopic ratios that help regulate the circadian system [23–25]. However, the quality and quantity of daylight in indoor spaces are affected by factors such as building envelope design, glazing types, and wall colours, highlighting the need to evaluate these aspects within indoor environments [3,23,26,27]. The calculation of illuminance levels is influenced by both the reflectance of interior surfaces and the type of windows and glazing through which natural light passes, which is why aesthetics are also important today [28]. The experience of facing a bright window versus a dimly lit wall can significantly affect well-being, as light (whether natural or artificial) interacts with interior surfaces, influencing how it is reflected, transmitted, or diffused. Furthermore, the type of window glazing significantly impacts the quality of indoor light, often necessitating artificial lighting to meet both visual and nonvisual requirements. Compliance with relevant lighting standards is necessary to maintain optimal illuminance levels and uniformity, thereby enhancing energy efficiency and achieving the desired aesthetic areas [29,30]. To quantify the biological potency of a light stimulus, different quantities are utilized, such as the melanopic equivalent daylight illuminance (mel-EDI) from CIE S 026 [16–18], and the equivalent melanopic lux (EML) from the WELL Building Standard v2 [20]. Therefore, according to standards, 750 lx are needed on the WP [21], while WELL standards recommend 275 EML at the VP [20].

This study focuses on analyzing the lighting conditions in a classroom by evaluating light transmission through different glazing types and the reflectance properties of wall and floor materials. Firstly, a spectral characterization was conducted for both transmittance (glazing) and reflectance (construction materials). Additionally, the spectral and spatial distributions of natural and artificial light sources were examined to identify suitable LED spectra for indoor lighting. The simulation aims to assess vertical and horizontal illuminance at various points in a classroom, including the WP and the VP, to determine an optimal combination of glazing and materials to meet the lighting requirements previously described. This paper presents an original contribution to the field of circadian lighting by specifically addressing the gap in understanding how different glazing transmittance levels and wall reflectance properties affect both photopic and melanopic lighting in educational environments. Previous studies have largely focused on general lighting conditions without adequately considering the spectral characteristics of materials and their impact on circadian rhythms. Our study is important because it provides a detailed analysis of these factors, using advanced simulation tools to offer new insights into optimizing both visual and non-visual lighting parameters in classrooms, which is critical for improving both comfort and well-being in indoor spaces.

2. Materials and Methods

2.1. Simulation Programs

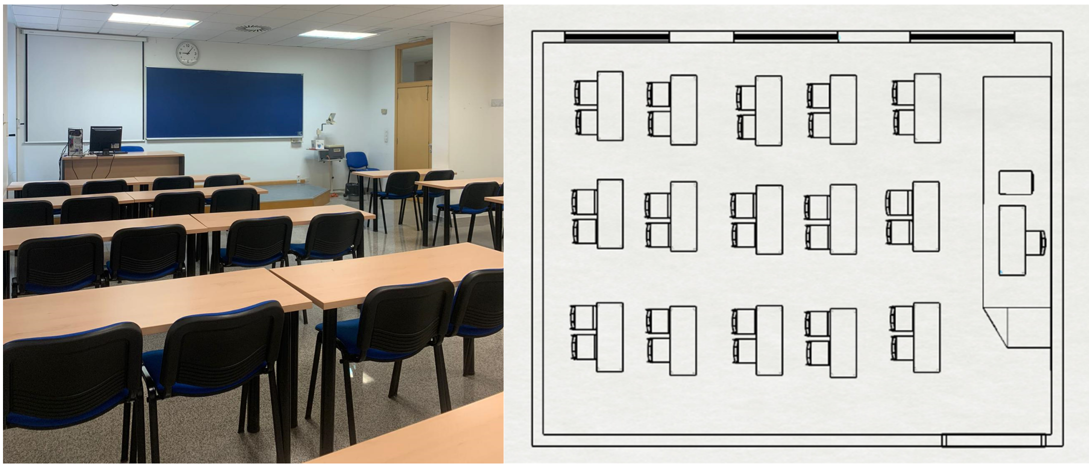
This study utilized a three-dimensional (3D) model of a classroom to evaluate the impact of glazing types and material reflectance on spatial characteristics. The design and simulations were conducted using distinct software tools. Firstly, Rhinoceros version 7 SR37 (Robert McNeel & Associates, Seattle, WA, USA), despite being a versatile 3D modeling software often used for more complex designs, was employed for initial classroom design. Secondly, ALFA version 0.6.0.0. Professional (Adaptive Lighting for Alertness) (Solemma LLC, Cambridge, MA, USA), an extension of Rhinoceros, was utilized for circadian lighting calculations, ensuring compliance with the WELL standard [20], this software facilitated precise measurement and control of non-visual effects of lighting, crucial for creating safer and more productive environments [31]. To obtain a manageable space in Rhino and the ALFA extension, it is necessary that both the classroom structure and all the furniture consist of surfaces to which a specific material can be assigned later. Thus, the first step was to create an accessible space to work with. The process was manual, every surface of the classroom was assigned a layer, which later allowed us to assign specific materials to each surface in the classroom, optimizing the vertical and horizontal illuminance levels to meet the necessary lighting requirements. These simulations were essential for meeting lighting requirements that support both visual comfort and occupant well-being, aligned with standards for WP illuminance [21] and WELL recommendations for VP circadian lighting [20].

2.2. Location and Classroom Model

The study focused on a classroom replica from the Faculty of Sciences at the University of Zaragoza, Zaragoza, Spain. This space was utilized for lectures throughout the entire academic schedule, thereby serving as a common area for both students and faculty. The simulated classroom dimensions were 6.80 m in width by 8.80 m in length, with the ceiling height at 3 m.

Figure 1 presents both the actual classroom that inspired the simulation and its 3D version in Rhino. It includes the teacher's desk along with a drawer unit and a chair on a platform 0.25 m high. Student desks are distributed throughout the classroom floor, and the ceiling houses only the luminaires. The real classroom features furniture made from materials common in public educational settings. The desks are wooden with a height of 0.73 m, the walls are white, a blackboard is positioned behind the professor's desk, and the floors are tiled in a neutral color.

Additionally, finding an appropriate classroom orientation is crucial, as a north-facing position would result in a space perpetually shaded from the sun, thereby receiving low illuminance from natural light [32]. To remain true to the real classroom, the simulated classroom is situated in Zaragoza (Latitude: 41.66°, Longitude: −0.88°) with the windowed wall facing east allowing for direct natural light to enter through the windows at an angle during the morning.

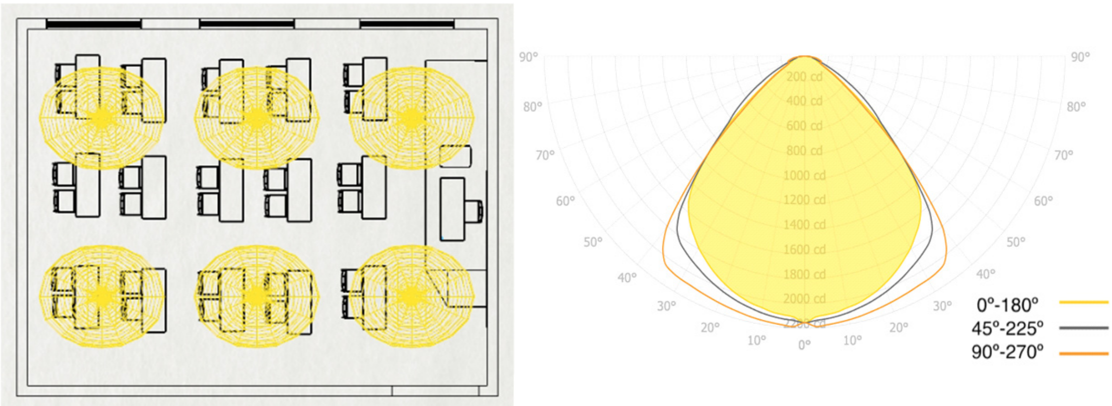


(**a**) (**b**)

Figure 1. Views of the modeled simulated classroom. (**a**) Real reference classroom; (**b**) 3D simulated classroom floor plan.

2.3. Luminaires

The positioning and distribution of the luminaires were arranged to match those in the real classroom. Six luminaires of the same type were symmetrically placed in the classroom, spaced apart at twice the distance from each other as they are from the wall. Figure 2a shows a schematic of this spatial arrangement. On the other hand, Figure 2b shows that the photometric curve of a single luminaire is symmetrical, being the same in the 0° and 180° planes. Figure 2a shows the simulated photometric curve in the classroom, illustrating how light is distributed when the lights are on. For spaces of this size, a luminaire with this type of symmetrical photometric curve is suitable because it distributes light evenly over the working area, minimizing significant differences in illuminance across different points.



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

Figure 2. Views of the modeled simulated classroom. (**a**): Luminaire arrangement in the classroom. (**b**): Photometric curve of the luminaire.

The selected luminaire was a ceiling-recessed linear fixture with lenses, measuring 0.61 m × 1.22 m, with a power consumption of 64 W and a luminous flux of 5700 lm. The chosen lamp for these luminaires was a continuous spectrum LED with a correlated color temperature (CCT) of 4966 K, and color render index (CRI) of 93, Figure 3 in blue, providing a color appearance that is intermediate but leaning towards cool, with an *M/P* ratio of 1.05, and Duv 0.0037, TM-30 Rf 93, Rg 98, Rcs,h_1 1%, Rf,h_1 97.

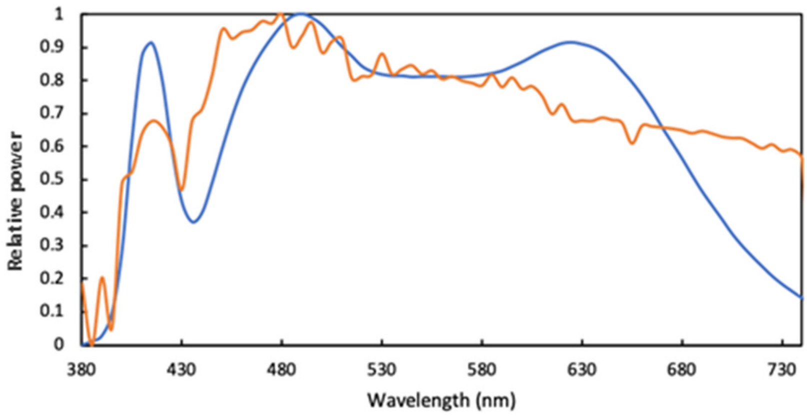


Figure 3. Normalized spectral power distribution of light sources used in the study: Emission spectrum of the LED, in blue, and emission spectrum of D65 (daylight), in orange.

The classroom was illuminated by two distinct light sources: daylight, referred to as the natural light source D65 under clear sky conditions (Figure 3, in orange), and the light from the installed luminaires, referred to as the artificial light (Figure 3, in blue). The selected date was 21 March, and the times were 11:00 AM for natural light simulations and 10:00 PM for nighttime. Given that the classroom faces east, the morning light entered the windows at a certain angle, but it still directly illuminated the classroom.

2.4. Material Assignment

Once the classroom was set up in the Rhino software, the next step was the selection of materials. The ALFA software provided an extensive list of materials to choose from, allowing for the assignment of reflectance to each of the surfaces that made up the classroom, as well as the required transmittance for the glazing [33]. Additionally, ALFA enables the creation of private material libraries where users can upload their own materials. Our goal was to use materials that result in a model closely resembling reality, therefore, reflectance data of various materials available within the university environment were collected using a calibrated CM-700d spectrophotometer (Konica Minolta Sensing Inc., Osaka, Japan) with a 2% uncertainty in reflectance measurements. This device allowed for the measurement of a material's reflectance by placing the colorimeter sensor near the material and taking the reading. It was a straightforward process that allowed measurements in two geometries: specular component included/excluded (SCI/SCE). Three measurements were taken for each selected material to obtain an average, and reflectance values were then imported into ALFA to apply them to the materials found in the real classroom for the simulation model. Reflectance measurements were taken from a total of 49 samples, including various shades of wooden furniture, the classroom window frame, different floors and walls, and ceiling panels to have different options and select the most appropriate ones (Table 1).

Table 1. Surfaces' reflectance: melanopic and photopic calculated under D65 illumination.

Surface	**R (%)**		**Surface**	**R (%)**	
	Melanopic	**Photopic**		**Melanopic**	**Photopic**
Chairs' seat	13.5	6.2	Students' tables	35.3	47.6
Teacher's chair seat	2.1	2.0	Blackboard	13.1	6.4
Drawer unit	37.0	39.8	Door	16.5	32.5
Metal drawer unit	12.6	11.9	Pallet	23.7	20.8
Window profile	62.9	63.5	Lift floor	12.6	11.9
Teacher's table	7.7	12.8	Ceiling	85.4	80.8

Therefore, it was essential to inventory the furniture and flat surfaces in the classroom, assigning a specific material to each. Two distinctions were made between the elements in the classroom: common elements and variable elements. Common elements remained constant regardless of the classroom model being simulated, while the variable elements were those where changes were made to obtain different results. This thorough material selection ensured that the simulation closely mirrored the actual classroom environment, leading to more accurate and reliable results that effectively reflect real-world scenarios and offer valuable insights for improving lighting design.

On the other hand, the non-common elements in the simulations included the walls, floor, and window glazing since three versions of the classroom were selected to obtain varying data. Henceforth, these classrooms will be referred to based on their material composition closest to the real classroom: white classroom, blue classroom, and red classroom. These classrooms differed primarily in the colors of their walls and floors, while the materials of the remaining elements stayed constant.

Figure 4b displays the spectral reflectance of the variable surfaces within the model itself, walls and floor, which determined the classroom names as previously indicated. The selection of these materials was made to ensure that the reflectance, especially those of the walls which characterize each classroom, clearly differentiates the illuminance measurement at various analysis points. The most noticeable difference can be observed in the curves that characterize the wall reflectance. For the blue classroom, a bluish color (Munsell 10BG 8/4), with 62% reflectance, was chosen with a greater spectral contribution in the short wavelength zones. For the red classroom, a light red color (MacBeth Light Skin) with a reflectance of 30% was selected, which, although leaning towards red, also has some spectral component in the blue. Lastly, the spectrum of the walls in the white classroom was continuous with the highest reflectance at 75%, based on measurements from the corridors of the Faculty of Sciences at the University of Zaragoza using the colorimeter.

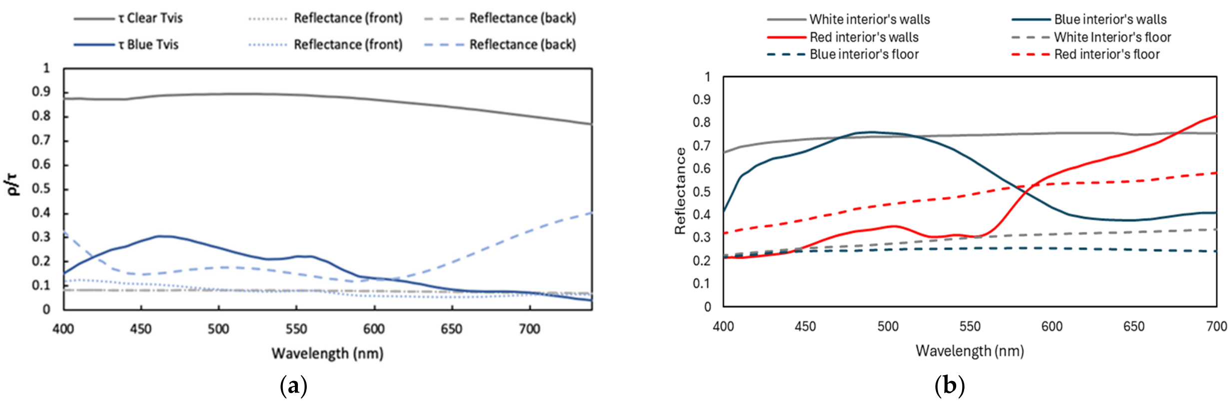


Figure 4. (**a**): transmittance and reflectance of glazing of Tvis 20% and Tvis = 88%. (**b**): walls' and floors' reflectance.

It is also important to highlight the window glazing. The simulations utilized two entirely different types of glazing, as shown in Figure 4a. The first was a glazing with 20% transmittance, visibly appearing bluish; the second was 88% transmittance, completely transparent in appearance. Figure 4 illustrates both the transmittance of the glazing and the reflectance of the back and front glass surfaces. These materials were part of the simulated classroom window, where the transmittance is crucial as it determines how much light passes through the glass. Additionally, during the simulations, reflections of light occurred on the interior glass surface, making the interior reflection factor of the glazing important for calculating illuminance on the study planes.

The 20% and 88% transmittance glazing were selected to evaluate a broad range of lighting conditions, from minimal to high daylight transmission, reflecting common real-world options. The 20% transmittance scenario, though less common, was included to study the effects of very limited daylight on lighting conditions and circadian responses. This comparison helps assess the impact of different transmittance levels on lighting performance, visual comfort, and energy efficiency and highlights the potential need for additional artificial lighting in scenarios with reduced natural light.

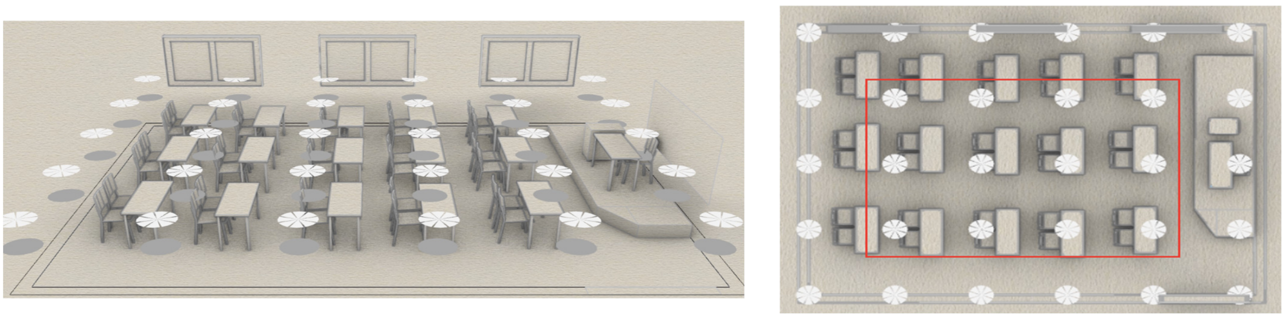
2.5. Simulated Scenarios

For each version of the classroom, simulations were conducted under three different lighting conditions using the two selected types of glazing. This means that for each classroom version, there were 6 different simulations, totaling 18 simulations overall. Table 2 provides a summary of the simulations conducted for each classroom version, labeled as Classroom Color, referring to each of the three classrooms described earlier, Table 2.

Table 2. Simulations analyzed for each colored classroom.

Type of Illumination	Glazing Transmittance
Daylight	20% and 88%
Daylight with luminaries turned on	20% and 88%
Nighttime with luminaries turned on	20% and 88%

To begin, the ALFA software allowed for the selection of the number of measurement points to be taken. These points were selected by adjusting a grid that modifies the spacing between each point. Specifically, 30 points spaced 1.7 m apart were available, but only 12 of these were utilized (area of interest inside the red rectangle). These points were positioned centrally within the classroom, as shown in Figure 5b.



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

Figure 5. Selected planes and points for taking measurements. (**a**): Classroom perspective with WP (gray circles) and VP (white circles). (**b**): Selected measurement points with VP sectors and red rectangle is the area of interest to be evaluated.

Each of these points allowed measurements on two different planes: the WP, positioned at a height of 0.80 m as per regulations (gray circles in Figure 5a), and the VP, positioned at eye level for a seated person, specifically at 1.20 m in height according to interior lighting standard and recommendations (white circles in Figure 5a) [20,21]. On the VP, each point was divided into eight sectors, which corresponded to the directions in which a seated person would be looking at. The points from which data were analyzed were within the red square, Figure 5b, indicating the sectors of the VP. The ALFA software provides the illuminance level (lx) on the WP, while only the EML values are displayed on the VP. These EML values can be converted to melanopic equivalent daylight illuminance (mel-EDI) using the formula: mel-EDI = 0.906 $\times$ EML [34].

During the simulations, six bounces were considered on each surface to obtain the results. Additionally, after conducting a series of checks related to the time required to complete the simulations, it was decided that each simulation would perform 500 steps (the number of discrete intervals the program uses to perform the simulation), based on the observation that the difference between 500 and 1000 steps was insignificant; 1000 steps took approximately 30 min, whereas 500 steps took about 6 min. This choice was made because the results obtained varied by a maximum of 2%.

ALFA provided a 3D visualization of the simulated space, Figure 6, the three versions of the classroom are presented under two scenarios: daytime with both natural and artificial light, and daytime only with natural light. It can be observed that the ones with lower quality compared to the others were due to increased noise in the visualization with higher light levels, resulting in poorer resolution. Despite this, a clear difference can be seen between each simulation.

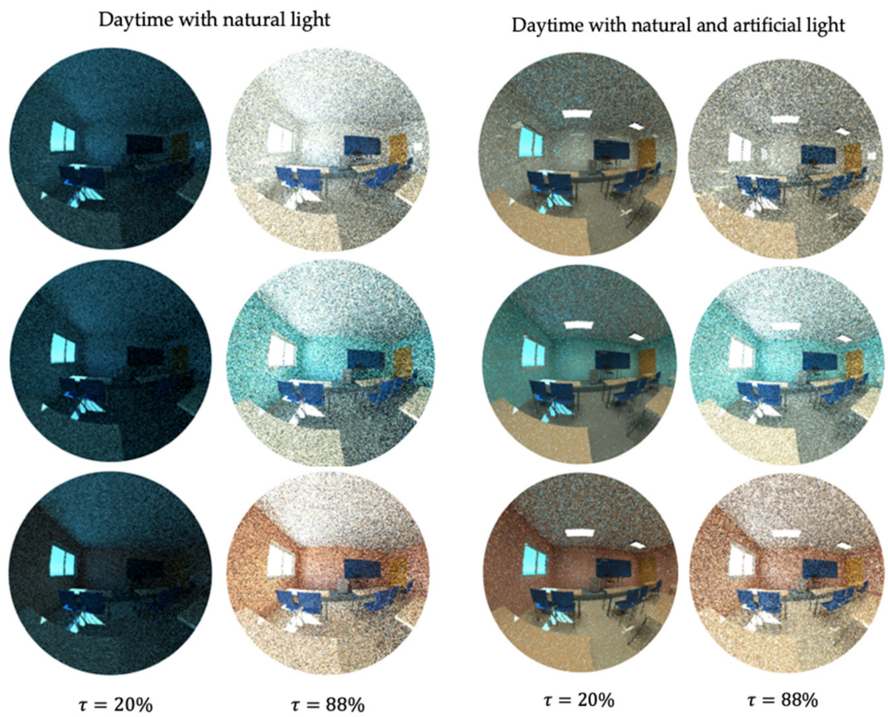


Figure 6. Simulated classroom by daytime, natural/artificial light, and transmittance of the glazing evaluation.

3. Results

The data from each classroom model is presented separately, allowing for an individual understanding of each situation, facilitating subsequent evaluation of the data collectively and enabling comparison between them. Each classroom undergoes six distinct simulations (Table 2). In all simulations, the evaluation process was standardized to ensure a clear representation of the data's range and variability, with a focus on identifying the points of maximum and minimum illuminance, and the mean values. The process began with a sweep across 12 points on the WP. A graph illustrating the behavior of all points was then generated, providing the necessary information to identify the maximum and minimum illuminance levels, and a parameter Ratio was defined to analyze the number of points reaching the minimum level of lighting required from the 12 points evaluated. Additionally, when solely artificial lighting was assessed, mean values and uniformity ($E_{\text{min}}/E_{\text{mean}}$ value) were calculated to evaluate compliance with interior lighting standards, however, when natural lighting was introduced, these parameters were not mandatory [21].

Regarding the VP, the process was more intricate since it was eight sectors from which to gather information (Figure 5b). The most relevant direction was where the student faces forward, typically towards the board. Therefore, the analysis focused exclusively on this direction. Similarly, 12 points were analyzed to quickly trace the maximums and minimums in this classroom plane, and mean values were calculated with exclusively artificial light. Data transcription was labor-intensive; each simulation yielded a data file containing not 12 but 30 points, so the 12 central points of interest were selected for each plane

(Figure 5b), excluding unused directions from the VP. This procedure was demonstrated in the initial analysis of the white classroom with natural lighting and without luminaires, with subsequent optimizations in the following analyses.

3.1. Daytime with Only Natural Light

For each situation, simulations were conducted with two types of glazing, with transmittances of 20% and 88%. In the three classrooms evaluated, with the luminaires off, the spectrum follows a trend closer to the transmittance of the glazing, modulated by the spectral power distribution (SPD) of the natural light used, and the same trend was observed in the spectrum of both planes, WP and VP, as expected (Figure 7). In the case of the VP, the illuminance was slightly higher than in the WP (Table 3), and the light levels between the maximum and minimum were more widely separated. On the other hand, in the WP, it was found that for some points, the function is approximately the same (<1% difference). The same procedure is carried out for the 88% glazing; the maximum and minimum values were selected for each plane and plotted together, differentiating each glazing type. In the red classroom, the numerical values are the lowest of all of them, Table 3.

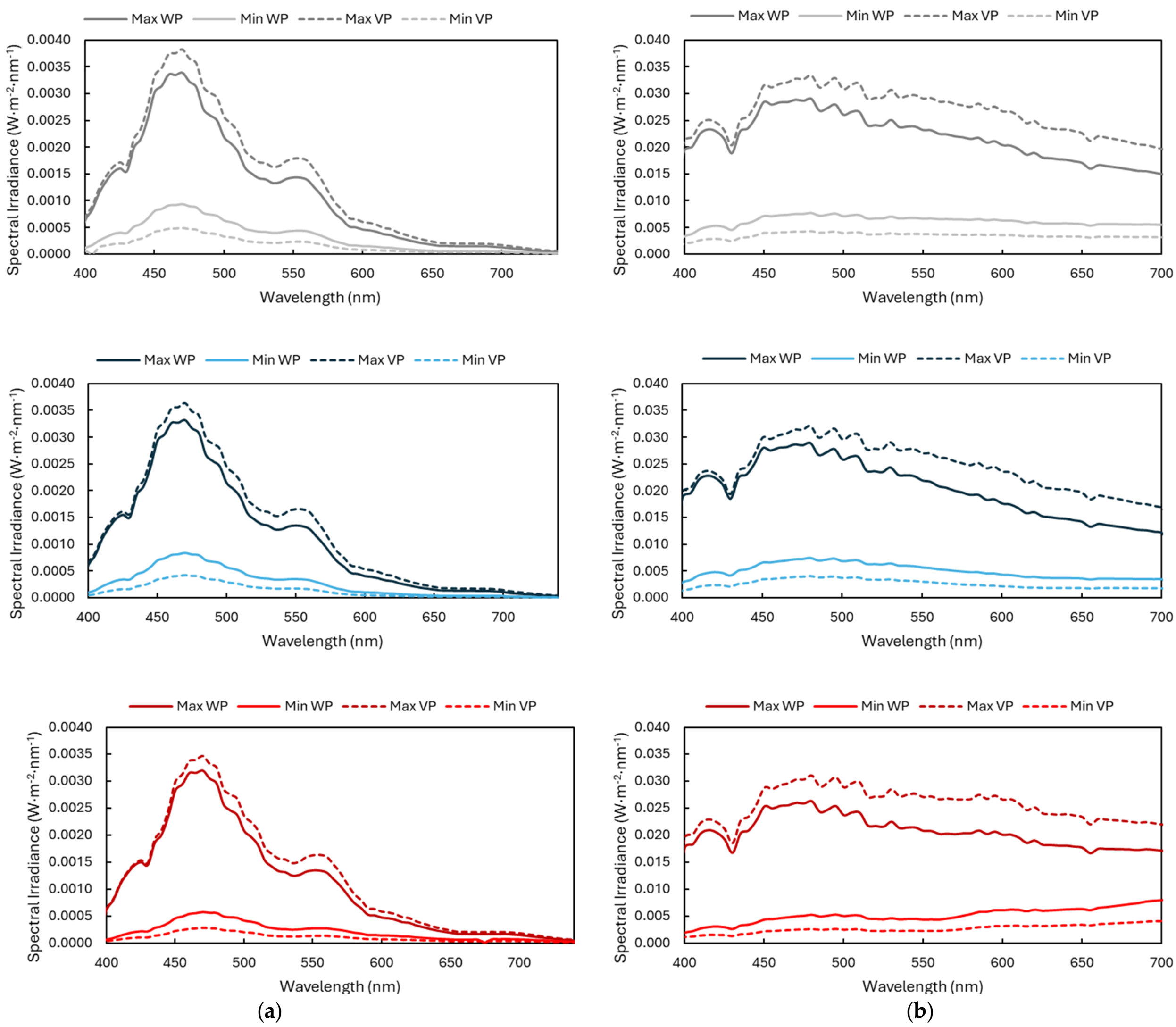


Figure 7. Lighting indoor the white/blue/red classrooms. (**a**): Indoor spectral power distribution (SPD) through glazing transmittance 20%. (**b**): Indoor SPD through glazing transmittance 88%. Max and Min values in dark and soft color, respectively.

Table 3. Classroom's illuminance values (lx) at the WP and EML at the VP, considering only daylight. E and EML mean values of photopic and melanopic light, respectively, and minimum and maximum values. Ratio value is the number of points evaluated that meet the requirements for VP and WP. Ratio *M/P (Method 3)* [35] is added to compare melanopic and photopic contributions.

		Workplane (WP)		Viewplane (VP)		
	τ (%)	**Ratio**	**E (E_{min}–E_{max}) (lx)**	**Ratio**	**EML (EML_{min}–EML_{max})**	**M/P Range**
White classroom	20	0	48 (26–86)	0	95 (25–197)	1.8–1.9
	88	7	922 (479–1647)	12	1090 (286–2232)	1.1
Blue classroom	20	0	42 (21–81)	0	90 (21–186)	1.9–2.1
	88	5	795 (389–1530)	11	1030 (252–2123)	1.1–1.3
Red classroom	20	0	40 (18–82)	0	79 (15–178)	1.7–1.8
	88	5	796 (369–1532)	11	943 (167–2068)	0.9–1.1

A significant difference can be seen between the SPD of the light obtained with each type of glazing at different points within the classroom. It is necessary to highlight that the spectrum of the 20% transmittance glazing generates illuminance spectra one order of magnitude lower than those of the 88% transmittance glazing (Figure 7, mean values in Table 3). Despite the differences in the spectra, the diagrams of the classrooms show that the maximum and minimum points occur at the same locations for each case; the maximum values are found near the windows, and the minimum values are in the lower right corner, in white and blue rooms. In the red room, although there are slight displacements, the maximum values are still positioned near the windows and the minimum values are in the furthest zone.

In Table 3, for the 20% glazing, values below the standard are obtained in all points evaluated (Ratio 0) for the white room in the WP with mean value 48 lx (range 26–86 < 750 lx) and below the recommended in the VP with mean value 95 EML (range 25–197 < 275 EML). It is resolved with the 88% transmittance glazing, which provides adequate results in 7 of the 12 points evaluated around the WP area, with a minimum value of 479 lx, a level sufficient enough to perform visual tasks (reading or writing) without problems. Ratio 12 is the VP since all the points evaluated reached the minimum level of 275 EML.

Equivalent results are found in the blue classroom in the WP (mean value 42 lx and range 21–81 < 750 lx) and in the VP (mean value 90, range 21–186 < 275 EML), and even more reduced in the red classroom both in the WP (mean value 40, range 18–82 < 750 lx) and in the VP (mean value 79, range 15–178 < 275 EML). In both rooms (blue and red), the issue is partially resolved by increasing the glazing transmittance to 88%, achieving mean values in both the WP (for blue: 795 lx and for red: 796 lx > 750 lx), and VP (for blue: 1030 EML and for red: 943 EML > 275 EML). However, this adjustment does not reach the optimal value in areas of minimum illumination for either the WP (for blue: 389 lx and for red: 369 lx < 750 lx) or the VP (for blue: 252 EML and for red: 167 EML < 275 EML) as shown in Table 3, although the parameter Ratio is increased significantly.

In both white and blue classrooms, the bluish appearance of the 20% transmittance glazing, since the light emitted in the low region of the visible spectrum favorably affects the circadian/photopic ratio (parameter *M/P*), improves the melanopic efficiency of this glazing compared to the 88% transmittance, despite the light levels reaching indoor points. It is worth noting that in the case of the red walls, its reflectance contributed the least to the circadian light, consequently reducing the values as Table 3 shows.

3.2. Daylighting and Artificial Lighting

The SPD curves with the maximum and minimum values for the classroom during the day with natural and artificial light are presented in Figure 8. The spectrum, as observed in all cases, follows the same trend for each type of glazing. Again, as can be seen in the diagrams of the graphs, the maximum values occur near the windows, while the minimum values for the 88% glazing remain in the same location as in the previous case. However, for the 20% glazing, the minimum values shift from their previous position, which can occur when the luminaires are turned on. The illuminance levels in this case are much higher than in the previous case due to the luminaires being on. This is particularly noticeable for the 20% glazing, where the SPD now resembles that of the luminaire due to the low transmittance of the glazing (Figure 3). Table 4 also shows the average values at each selected point; it can also be observed that in the white classroom with 20% glazing, the values do not meet the standards (Ratio 0) for the WP (mean value 582, range 408–687 < 750 lx) but adhere to the recommendations for the VP (mean value 315, range 184–580 > 275 EML in 7 points).

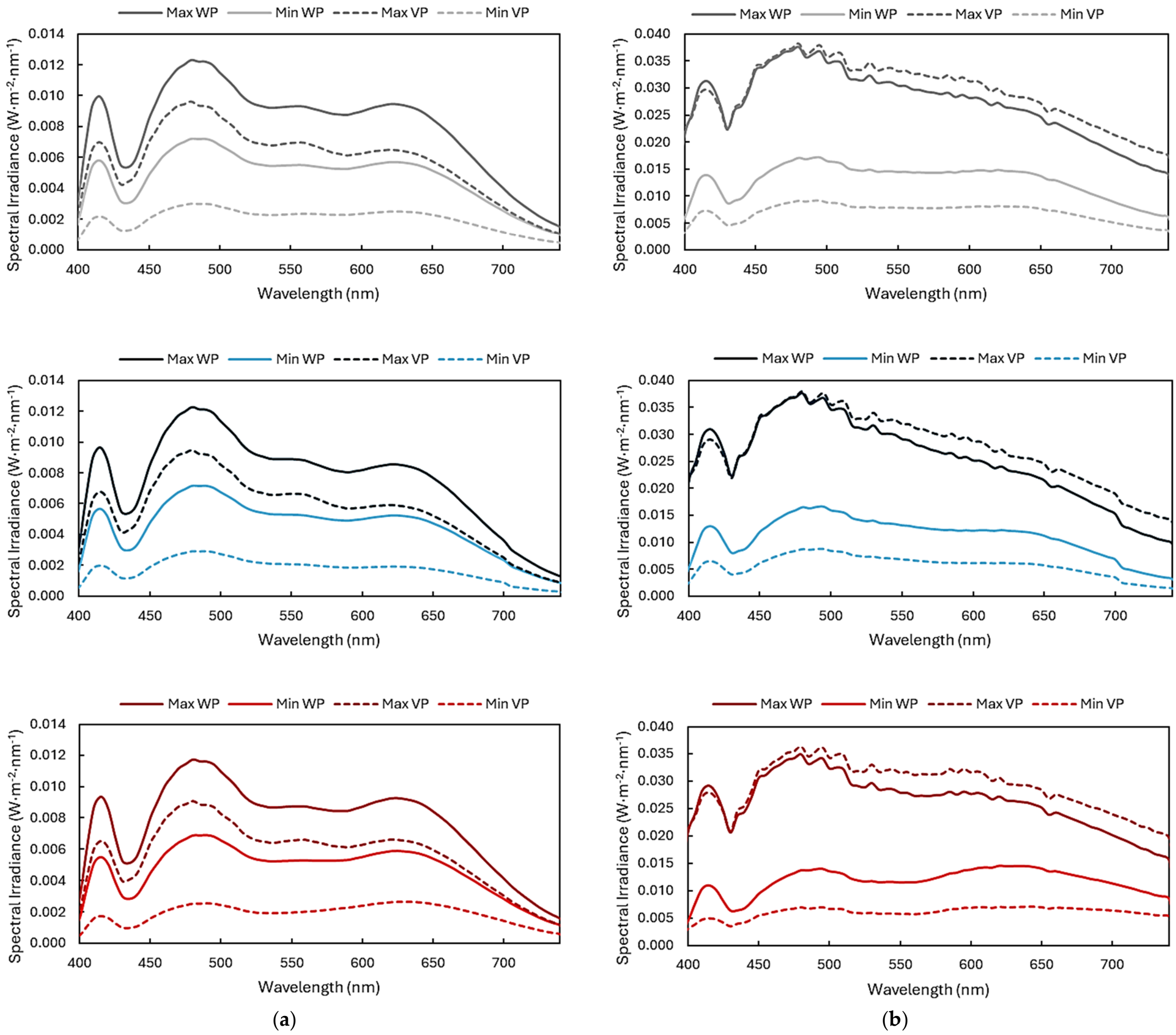


Figure 8. Daylighting and artificial lighting indoor the white/blue/red classrooms. (**a**): Indoor spectral power distribution (SPD) through glazing transmittance 20%. (**b**): Indoor SPD through glazing transmittance 88%. Max and Min values in dark and soft color, respectively.

When changing the glazing by 88% in the white classroom, it can be observed that the Ratio is 12 in both the WP (mean value 1419, range 1144–2202 lx), and in the VP (mean value 1246, range 588–2527 EML), as it is indicated in Table 4. It has been demonstrated that high reflectivity in the materials of a space has a significant impact on the illuminance measured on the corneal plane, VP. Therefore, in the case of the VP, the values are higher because more light enters through the windows and with the lights on, the walls affect the illuminance measured in the VP to a greater extent.

Table 4. Classroom's illuminance values (lx) at the WP and EML at the VP, considering daylight and artificial light. E and EML mean values of photopic and melanopic light, respectively, and minimum and maximum values. Ratio value is the number of points evaluated that meet the requirements for VP and WP. Ratio *M/P (Method 3)* [35] is added to compare melanopic and photopic contributions.

		Workplane (WP)		Viewplane (VP)		
	τ (%)	Ratio	E (E_{min}–E_{max}) (lx)	Ratio	EML (EML_{min}–EML_{max})	M/P Range
White classroom	20	0	582 (408–687)	7	315 (184–580)	1.1–1.2
	88	12	1419 (1144–2002)	12	1246 (588–2527)	1.0–1.1
Blue classroom	20	0	559 (389–651)	6	302 (175–567)	1.2
	88	12	1277 (958–2075)	12	1209 (545–2490)	1.0–1.1
Red classroom	20	0	562 (399–652)	5	282 (154–548)	1.0–1.1
	88	12	1291 (916–2070)	12	1116 (452–2407)	1.0

For the blue and red classrooms compared to the white classroom, the measured illuminances in both planes are slightly lower, indicating the change perceived when modifying the wall and floor materials. The maximum and minimum values remain in the same locations as in the equivalent case for the white classroom. Again, for 20% glazing, the maximum values would be slightly below compliance with the standard in the WP (both < 750 lx), while they would meet the requirements in the VP (both > 275 EML), but the minimum values would not do so in either the WP or the VP. On the other hand, for 88% of the glazing, the illuminance is adequate in all cases with Ratio 12 (Table 4).

As in the white classroom and the blue classroom, in the red classroom with the 20% glazing, they can find SPDs are spectrally similar. The maximum values for all types of glazing remain in the area near the windows where the light is more direct. The minimum values, however, shift to different points compared to those observed in the previous classrooms, although no more than two positions from the other classrooms. As in the previous cases, the red classroom is now better lit, but the areas where the minimum values occur for both the WP (399 lx) and the VP (154 EML) show very low illuminance values. For the 88% glazing, the lighting is adequate when the red walls are considered for the WP (mean value 1291 lx, range 916–2070 lx) and the VP (mean value 1116, range 452–2407 EML), although all values are still the lowest with respect to the white and blue classrooms.

In this instance, the *M/P* ratio is approximately 1, indicating a more balanced SPD of the evaluated light sources. However, under specific spectral configurations, particularly in the white and blue light ranges, *M/P* ratios as high as 1.2 can be achieved.

3.3. Nighttime with Only Artificial Light

Lastly, simulations were conducted at night with the luminaires on for the white, blue, and red classrooms, considering the two types of glazing. As expected, all scenarios yielded similar results due to the absence of natural light, which does not affect the illuminance calculations. Although light from the luminaires can reflect off the glazing, this reflection is negligible, resulting in consistent outcomes across all simulations. Therefore, a single graph representing the simulations for each classroom is shown in Figure 9. In all classrooms, the maximum values are found near the windows, with the minimum values for the VP also located there. These positions are influenced solely by the luminaires' locations and the distribution of light in the classrooms. The SPD of the chosen LED luminaires can be observed, highlighting the most illuminated points, as natural light is not a factor in these measurements.

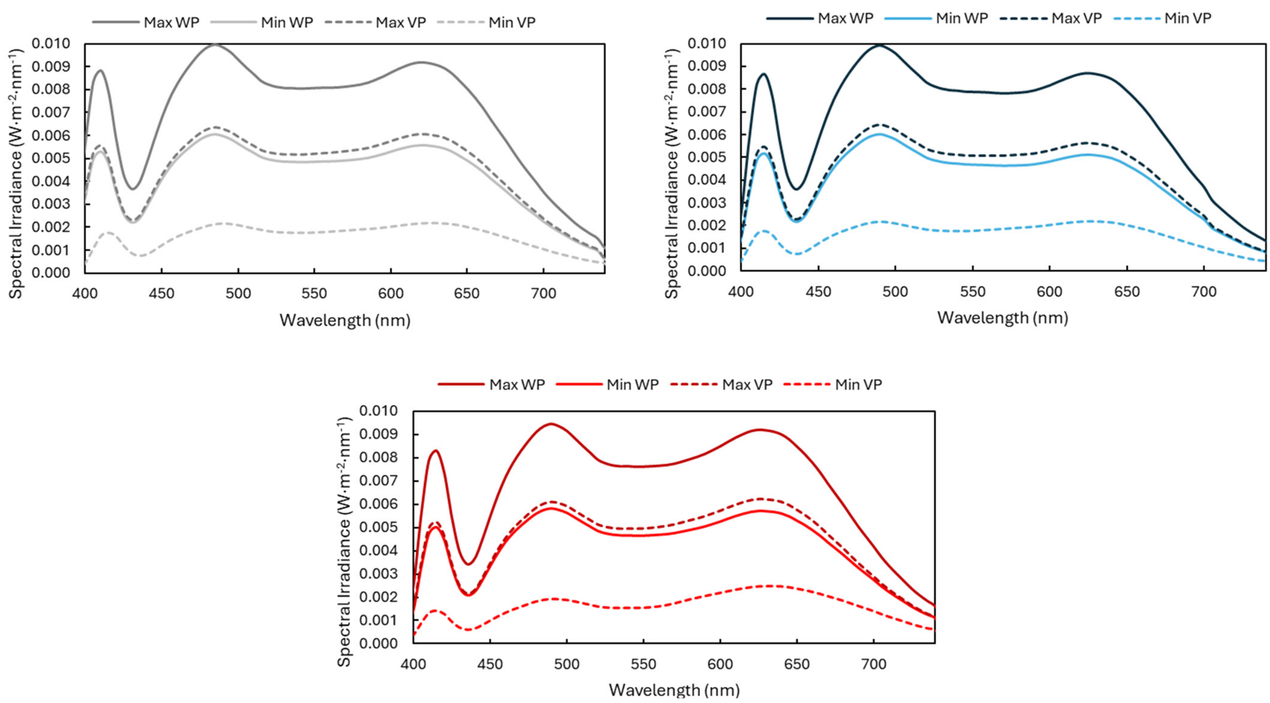


Figure 9. Artificial lighting indoor the white/blue/red classrooms, no transmittance considered to plot maximum and minimum values (in dark and soft color, respectively).

The numerical data, shown in Table 5 for the white classroom, are indicative of the photopic and melanopic contributions when the lights are on, revealing that the EML (mean value 220, range 131–387 EML) in the VP and E (mean value 538, range 369–611 lx) values in the WP are of the same order, and the *M*/*P* ratio is 1.0. Similar results are observed in the blue and red classrooms, with slight variations due to the different reflectance properties of their wall and floor materials. In the blue classroom, a shift in the positions of the maximum and minimum values is noted, caused by the reflectance properties of the new materials (Table 5). Despite these shifts, the lighting remains inadequate in all classrooms, Ratio 0, as the luminaires fail to meet the standard requirement of >750 lx in the WP, as the Ratio-value results display, despite having a uniformity value of 0.7, which exceeds the 0.6 threshold established by the standard [21]. In the red classroom, the illuminance values are like those in the other two classrooms, with a notable difference in the maximum WP (590 lx) value due to the materials being the least reflective. This difference, however, does not exceed 10%. The *M*/*P* ratio (range 0.9–1.0) and the positions of the maximum and minimum values remain consistent for the red classroom with those in the white and blue classrooms, confirming that none of the classrooms are adequately lit for performing work.

Table 5. Classroom's illuminance values (lx) at the WP and EML at the VP, considering only artificial light. E and EML mean values of photopic and melanopic light, respectively, and minimum and maximum values. Ratio value is the number of points evaluated that meet the requirements for VP and WP. Ratio *M/P (Method 3)* [35] is added to compare melanopic and photopic contributions. Uniformity (E_{min}/E) of the distribution of the light in the WP.

		Workplane (WP)			Viewplane (VP)		
	τ (%)	Ratio	Uniformity	E (E_{min}–E_{max}) (lx)	Ratio	EML (EML_{min}–EML_{max})	M/P Range
White classroom	20/88	0	0.7	538 (369–611)	4	220 (131–387)	1.0
Blue classroom	20/88	0	0.7	519 (353–595)	4	215 (125–389)	1.0–1.1
Red classroom	20/88	0	0.7	524 (363–590)	4	199 (114–370)	0.9–1.0

As a resume of the ranges of lighting found, Figure 10 shows how levels of the analyzed situations are distributed along the area of interest, reaching the highest values of light in different points when evaluating the WP or the VP. These variations not only depend on the type of light and spectral characteristics of the materials employed, but also other considerations are necessary, such as the spatial distribution curve of the selected luminaries, the number of them, or their position from the evaluated points.

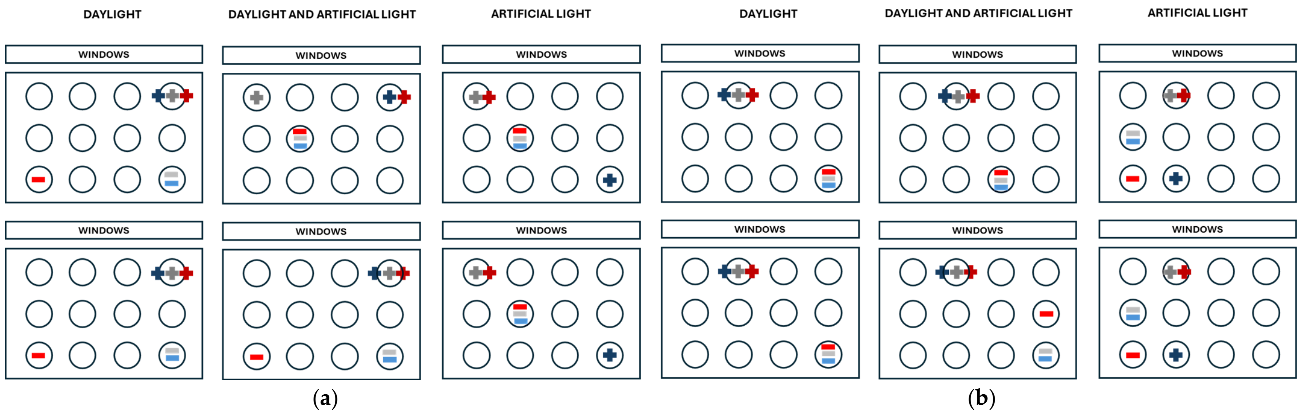


Figure 10. Upper/lower τ = 20% and 88%, respectively. (**a**): Work Plane. (**b**): View Plane. Symbols (+) and (−) indicate maximum and minimum levels of light, respectively. Colors gray/blue/red for white/blue/red classrooms.

4. Discussion

The analysis of natural daylight behavior in classrooms with different glazing types reveals significant variations in SPD and illuminance levels with potential impact in both the visual and non-visual systems [3]. The study compares three different colored wall classrooms under clear sky conditions (6500 K), utilizing two distinct glazing types: one with 20% transmittance and the other with 88% transmittance.

Firstly, in classrooms lit exclusively by daylight entering through the windows, our results show significant variations in SPD at different points within the rooms. These variations affect not only the calculated light levels and uniformity of the WP but also potentially influence the color of the environment, visual comfort, and task performance of the occupants [12,36–38]. As shown in Table 3, the white classroom exhibits the highest maximum and minimum photopic illuminance at the WP. This pattern aligns with the higher reflectance properties of white surfaces, which enhance room brightness and increase illuminance at measured points. Although the range of minimum-maximum illuminance levels is proportional in the three scenarios, the obtained results pointed out that the proper selection of other materials different from white could be identically appropriate depending on the purpose of the room [39]. The 20% transmittance glazing restricts visible light; despite these conditions, an *M/P* ratio range from 1.7 to 1.8 is achieved even in the red scenario due to the relatively high transmittance of the glazing in the shorter wavelengths of the spectrum, providing extremely high values of circadian light relative to the photopic level spite of the color of the walls, achieving comparable melanopic levels at the VP in the three classrooms. In contrast, classrooms with 88% transmittance glazing exhibit a different behavior, as illustrated in Figure 7, this glazing type closely mimics the daylight spectrum (illuminant D65), as its high transmittance allows the entire spectrum to penetrate. Consequently, light entering these classrooms maintains elevated levels across all wavelengths, unlike the 20% transmittance scenario. Maximum illuminance values across all classrooms show minimal variation (within 10%), indicating that while overall illuminance is maximized, spectral variations are still present based on specific spectrum areas. The proper selection of glazing appears to be more critical, as a transmittance of 88% is required to achieve adequate EML levels in at least 11 out of the 12 evaluated points at the corneal plane and to ensure that the light levels in the WP are sufficient in at least half of the analyzed points. Consequently, from a quantitative point of view, the illuminance levels differ significantly between the two glazing types; classrooms with 20% transmittance glazing allow minimal light penetration, resulting in illuminance values one order of magnitude lower compared to those with 88% transmittance glazing. This stark difference highlights the critical role of glazing properties in modulating natural light's impact on indoor environments [38,40]. Despite different glazing transmittance levels, the maximum and minimum illuminance points remained the same due to the classroom's layout and the influence of internal reflections, which outweighed the impact of glazing on light distribution.

The integration of natural and artificial lighting in classrooms with different glazing transmittance levels reveals important insights into how these factors affect indoor illumination and spectral distribution [3,30]. When indoor LEDs are used with 20% transmittance glazing, the resulting spectrum within the classrooms closely resembles the LED spectrum because the glazing restricts most exterior natural light, allowing the LED light to dominate. Despite these spectral variations, the white classroom achieves again the best overall illumination, consistent with its higher reflectance properties which enhance brightness. However, in none of the three scenarios does the light level on the WP reach the minimum 750 lx required by the standard [21] and only in half of the evaluated points in the VP [20]. Conversely, with 88% transmittance glazing, the spectrum within the classrooms is predominantly influenced by natural sunlight due to its higher energy compared to the LED light. This indicates that while natural light has a more substantial presence, the distribution of light within the visible spectrum varies significantly based on the classroom's color and reflectance properties. In these scenarios, regardless of the wall reflectance, both the WP and the VP are consistently illuminated at all evaluated points. This configuration is optimal, as the points that were not adequately illuminated solely by daylight (particularly those farther from the windows) receive sufficient illumination when artificial light is introduced. Interestingly, with artificial lighting on, the numerical differences in illumination between the three glazing types are not as pronounced as when only natural light is considered. Even with 20% transmittance glazing, the classrooms achieve better illumination, suggesting that the addition of LED lighting can compensate for the limited natural light transmittance, achieving a level of photopic light (>300 lx) and melanopic light (>150 EML) that could be enough to perform determinate tasks without excessive requirements around the classroom [20,21].

The nighttime simulations of the three classrooms under artificial LED lighting reveal important insights into indoor lighting conditions and their alignment with the established standards [20,21]. Without the influence of sunlight, the spectral behavior replicates the LED spectrum. The contribution of the front reflectance of the glazing is comparable in both types of windows and, as observed in Figure 9, the slight shifts are present. With these conditions, the results indicate that nighttime illumination with the current LED setup does not meet completely the required standards for adequate classroom lighting, since none of the points on the WP reach the established 750 lx, but its uniformity along the plane is excellent (>0.6), and slight differences attending on the reflectance of the wall are found [21]. This highlights the need for either changing the lighting system or supplementing it to ensure proper illumination in these dim lighting conditions, pointing out the equivalence of the levels reached with the different environments [39,40].

As a whole, this study involved the design and realistic illumination of three classroom models closely resembling real-life educational spaces. The selection of materials for glazing, walls, and floors was tailored to this application, and a low transmittance glazing of 20% was chosen to emphasize the importance of window characteristics on interior lighting, which resulted in a significant reduction of natural light and a decrease in photobiological contributions. The lower illuminance in the red classroom reduces visibility and comfort, potentially hindering learning tasks compared to the brighter white and blue classrooms, which offer better lighting and visual comfort. The extreme wall color of the red classroom was selected to further explore material reflectance. However, the reflectance of the red material, which included a blue component, resulted in less differentiation in spectral calculations than initially expected. The impact of wall reflectance spectra on photopic and melanopic functions shows that the white classroom provides the best illumination across all simulations, while the red classroom offers the worst. However, the differences are not substantial, within a maximum difference of 10%, suggesting similar conditions across the classrooms. Circadian lighting levels are higher in classrooms with highly reflective walls or those reflective in the short wavelength range but remain insufficient for adequate circadian stimulation in low transmittance scenarios according to current recommendations [39]. The study also reaffirms the reliability of ALFA software for simulating and evaluating photopic and melanopic levels in integrative lighting projects due to its spectral analysis [41]. This makes both the described method and the evaluated parameters representative of the most influential factors in an integrative lighting project positioning ALFA as a proper software for this purpose since it calculates the evaluated magnitudes based on $\rho(\lambda)$, $\tau(\lambda)$, and SPD [31]. Not only the lighting level at the calculation point is important, but also the spectral characteristics of the space materials [28,39,40], the type of artificial light used [26], the natural light modified by the transmittance of the windows [3,32], or the location of the evaluation point within the room to optimize the process and resulting values [42].

5. Conclusions

This study highlights the critical role of glazing materials in optimizing natural daylight utilization in educational settings. Higher transmittance glazing significantly enhances indoor illuminance and maintains a natural light spectrum, benefiting both visual and non-visual aspects of occupant well-being. However, artificial lighting can effectively compensate for lower transmittance glazing, improving indoor illumination levels. The research emphasizes the need to consider both natural and artificial lighting in designing educational spaces to achieve optimal visual comfort and performance. Key factors include the spectral characteristics of materials, the type of artificial light, window transmittance, and the location of evaluation points within the room.

The primary limitation of this study lies in its focus on a narrow set of configurations within a single classroom environment located in Zaragoza. The use of standard materials and a controlled, singular scenario was a deliberate choice to ensure precision and reproducibility, but it inherently restricts the generalizability of the findings. As a result, the conclusions drawn are specific to the conditions simulated and may not fully capture the complexities of real-world applications and other layouts should be considered to provide a more comprehensive understanding of how different spatial arrangements and material properties affect lighting performance and visual comfort in various environments.

To address these limitations and enhance the applicability of the findings, future research should expand the scope of the study to include a broader range of configurations, including different room orientations, layouts, and material properties. Additionally, using software other than ALFA may be necessary, as it does not provide mel-EDI values in accordance with CIE standards, offering only EML values instead. Incorporating empirical measurements alongside simulations would provide valuable validation and improve the robustness of the results. Additionally, exploring the impact of varied lighting conditions in diverse environments, such as different types of classrooms or other indoor spaces, would offer a more comprehensive understanding of how these factors influence lighting performance and visual comfort across various settings. Other future research could explore how differences in the SPD between the 88% and 20% transmittance glazing affect visual comfort, eye strain, and students' ability to focus. Besides, the bluish tint of 20% transmittance glazing alters color perception in the classroom, impacting how colors are rendered; this effect could be considered in future studies focused on visual perception. This expanded research could contribute significantly to the development of more versatile and effective lighting design strategies. It could refine lighting systems to better meet standards, considering both photopic and melanopic needs.

Author Contributions: Conceptualization, E.O.-H., J.A. and A.S.-C.; methodology, E.O.-H., J.A. and A.S.-C.; formal analysis, I.E., E.O.-H., J.A. and A.S.-C.; investigation, I.E., E.O.-H., J.A. and A.S.-C.; data curation, I.E. and A.S.-C.; writing—original draft preparation, I.E., E.O.-H., J.A. and A.S.-C.; writing—review and editing, I.E., E.O.-H., J.A. and A.S.-C.; visualization I.E., E.O.-H., J.A. and A.S.-C.; supervision, J.A. and A.S.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by UZ2023-CIE-06 project from the University of Zaragoza.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Schlangen, L.J.M.; Price, L.L.A. The Lighting Environment, Its Metrology, and Non-Visual Responses. *Front Neurol.* **2021**, *12*, 624861. [CrossRef] [PubMed]
2. Duffy, J.F.; Czeisler, C.A. Effect of Light on Human Circadian Physiology. *Sleep Med. Clin.* **2009**, *4*, 165–177. [CrossRef]
3. Ghaeili Ardabili, N.; Wang, J.; Wang, N. A Systematic Literature Review: Building Window's Influence on Indoor Circadian Health. *Renew. Sustain. Energy Rev.* **2023**, *188*, 113796. [CrossRef]
4. Brainard, G.C.; Hanifin, J.P.; Greeson, J.M.; Byrne, B.; Glickman, G.; Gerner, E.; Rollag, M.D. Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor. *J. Neurosci.* **2001**, *21*, 6405–6412. [CrossRef]
5. Jalali, M.S.; Jones, J.R.; Tural, E.; Gibbons, R.B. Human-Centric Lighting Design: A Framework for Supporting Healthy Circadian Rhythm Grounded in Established Knowledge in Interior Spaces. *Buildings* **2024**, *14*, 1125. [CrossRef]
6. Manfredini, R.; Cappadona, R.; Tiseo, R.; Bagnaresi, I.; Fabbian, F. Light, Circadian Rhythms and Health. In *Therapeutic Landscape Design: Methods, Design Strategies and New Scientific Approaches*; Capolongo, S., Botta, M., Rebecchi, A., Eds.; Springer International Publishing: Cham, Switzerland, 2023; pp. 81–92. ISBN 978-3-031-09439-2.
7. Court, L. Light and Visible Radiation. 2012. ISBN 9782817803630. Available online: https://www.ncbi.nlm.nih.gov/books/NBK304366/ (accessed on 17 July 2023).
8. Wyszecki, G.; Stiles, W.S. *Concepts and Methods, Quantitative Data and Formulae*; John Wiley & Sons: Hoboken, NJ, USA, 1982; p. 9.
9. Sanchez-Cano, A.; Orduna-Hospital, E.; Fernández-Espinosa, G.; Aporta, J. Method to Calculate Melanopic Light Reaching the Retina Depending on the Optical Density of an Aging Crystalline Lens. *Appl. Sci.* **2023**, *13*, 2569. [CrossRef]
10. Lucas, R.J.; Peirson, S.N.; Berson, D.M.; Brown, T.M.; Cooper, H.M.; Czeisler, C.A.; Figueiro, M.G.; Gamlin, P.D.; Lockley, S.W.; O'Hagan, J.B.; et al. Measuring and Using Light in the Melanopsin Age. *Trends Neurosci.* **2014**, *37*, 1–9. [CrossRef]
11. Houser, K.W.; Esposito, T. Human-Centric Lighting: Foundational Considerations and a Five-Step Design Process. *Front Neurol.* **2021**, *12*, 630533. [CrossRef] [PubMed]
12. Nazari, M.; Matusiak, B.; Stefani, O. Utilising Spectral Lighting Simulation Technique for Evaluating Transmitted Daylight through Glazing: Exploring the Non-Visual Effects and Colour Appearance. *Heliyon* **2023**, *9*, e20436. [CrossRef]
13. Gooley, J.J.; Lu, J.; Chou, T.C.; Scammell, T.E.; Saper, C.B. Melanopsin in Cells of Origin of the Retinohypothalamic Tract. *Nat. Neurosci.* **2001**, *4*, 1165. [CrossRef]
14. Husse, J.; Eichele, G.; Oster, H. Synchronization of the Mammalian Circadian Timing System: Light Can Control Peripheral Clocks Independently of the SCN Clock: Alternate Routes of Entrainment Optimize the Alignment of the Body's Circadian Clock Network with External Time. *BioEssays* **2015**, *37*, 1119–1128. [CrossRef] [PubMed]
15. Kofuji, P.; Mure, L.S.; Massman, L.J.; Purrier, N.; Panda, S.; Engeland, W.C. Intrinsically Photosensitive Retinal Ganglion Cells (IpRGCs) Are Necessary for Light Entrainment of Peripheral Clocks. *PLoS ONE* **2016**, *11*, e0168651. [CrossRef] [PubMed]
16. *CIE S 026/E:2018*; CIE System for Metrology of Optical Radiation for IpRGC-Influenced Responses to Light. CIE: Vienna, Austria, 2018.
17. CIE Position Statement on Integrative Lighting Recommending Proper Light at the Proper Time, 3rd ed. Available online: https://cie.co.at/publications/cie-position-statement-integrative-lighting-recommending-proper-light-proper-time-3rd (accessed on 17 July 2024).
18. CIE Position Statement on Non-Visual Effects of Light Recommending Proper Light at the Proper Time, 2nd ed. 2019. Available online: https://cie.co.at/publications/position-statement-non-visual-effects-light-recommending-proper-light-proper-time-2nd (accessed on 17 July 2024).
19. *ANSI/IES TM-30-24*; IES Method for Evaluating Light Source Color Rendition. Illuminating Engineering Society: New York, NY, USA, 2018.
20. IWBI International Well Building Institute. WELL Building Standard v2 Pilot, Q3 2021 Version. *Section L03: Circadian Lighting Design 2021*. Available online: https://v2.wellcertified.com/en/wellv2/light/feature/3 (accessed on 17 July 2024).
21. UNE-EN 12464-1:2022 Light and Lighting—Lighting of Work Places—Part 1: Indoor Work Places. Available online: https://www.une.org/encuentra-tu-norma/busca-tu-norma/norma?c=N0068596 (accessed on 17 July 2024).

22. Esquiva, G.; Lax, P.; Pérez-Santonja, J.J.; García-Fernández, J.M.; Cuenca, N. Loss of Melanopsin-Expressing Ganglion Cell Subtypes and Dendritic Degeneration in the Aging Human Retina. *Front Aging Neurosci.* **2017**, *9*, 79. [CrossRef]
23. Potočnik, J.; Košir, M. Influence of Commercial Glazing and Wall Colours on the Resulting Non-Visual Daylight Conditions of an Office. *Build Environ.* **2020**, *171*, 106627. [CrossRef]
24. Aguilar-Carrasco, M.T.; Dominguez-Amarillo, S.; Acosta, I.; Sendra, J.J. Indoor Lighting Design for Healthier Workplaces: Natural and Electric Light Assessment for Suitable Circadian Stimulus. *Opt. Express.* **2021**, *29*, 29899–29917. [CrossRef]
25. Hraska, J. Chronobiological Aspects of Green Buildings Daylighting. *Renew. Energy* **2015**, *73*, 109–114. [CrossRef]
26. Ezpeleta, S.; Orduna-Hospital, E.; Solana, T.; Aporta, J.; Pinilla, I.; Sánchez-Cano, A. Analysis of Photopic and Melanopic Lighting in Teaching Environments. *Buildings* **2021**, *11*, 439. [CrossRef]
27. Šprah, N.; Potočnik, J.; Košir, M. The Influence of Façade Colour, Glazing Area and Geometric Configuration of Urban Canyon on the Spectral Characteristics of Daylight. *Build. Environ.* **2024**, *251*, 111214. [CrossRef]
28. Cai, W.; Yue, J.; Dai, Q.; Hao, L.; Lin, Y.; Shi, W.; Huang, Y.; Wei, M. The Impact of Room Surface Reflectance on Corneal Illuminance and Rule-of-Thumb Equations for Circadian Lighting Design. *Build. Environ.* **2018**, *141*, 288–297. [CrossRef]
29. Mahmoudzadeh, P.; Hu, W.; Davis, W.; Durmus, D. Spatial Efficiency: An Outset of Lighting Application Efficacy for Indoor Lighting. *Build. Environ.* **2024**, *255*, 111409. [CrossRef]
30. Alkhatatbeh, B.J.; Kurdi, Y.; Asadi, S. Multi-Objective Optimization of Classrooms' Daylight Performance and Energy Use in U.S. Climate Zones. *Energy Build.* **2023**, *297*, 113468. [CrossRef]
31. Bellia, L.; Błaszczak, U.; Diglio, F.; Fragliasso, F. Assessment of Melanopsin-Based Quantities: Comparison of Selected Design Tools and Validation against on-Field Measurements. *Build. Environ.* **2023**, *232*, 110037. [CrossRef]
32. Ezpeleta, S.; Orduna-Hospital, E.; Aporta, J.; Luesma, M.J.; Pinilla, I.; Sánchez-Cano, A. Evaluation of Visual and Nonvisual Levels of Daylight from Spectral Power Distributions Considering Orientation and Seasonality. *Appl. Sci.* **2021**, *11*, 5996. [CrossRef]
33. Jakubiec, J.A. Data-Driven Selection of Typical Opaque Material Reflectances for Lighting Simulation. *LEUKOS-J. Illum. Eng. Soc. North Am.* **2023**, *19*, 176–189. [CrossRef]
34. Sánchez-Cano, A.; Aporta, J. Optimization of Lighting Projects Including Photopic and Circadian Criteria: A Simplified Action Protocol. *Appl. Sci.* **2020**, *10*, 1–19. [CrossRef]
35. Miller, N.J.; Irvin, A. M/P Ratios: A Call for Consistency. *LD+ A Mag.* **2020**, *50*, 12–14.
36. Katunský, D.; Dolníková, E.; Dolník, B.; Krajníková, K. Influence of Light Reflection from the Wall and Ceiling Due to Color Changes in the Indoor Environment of the Selected Hall. *Appl. Sci.* **2022**, *12*, 5154. [CrossRef]
37. Fontana, L. Effect of Indoor Surfaces' Spectral Reflectance on the Environmental Light Spectrum Modification and on Objects Perceived Color. *Results Eng.* **2023**, *17*, 100805. [CrossRef]
38. Liu, D.; Kovacs-Biro, M.J.; Connelly, K.; Abd-AlHamid, F.; Wu, Y. Preliminary Investigation on the Human Response to Patterned Chromatic Glazing. *Build. Environ.* **2023**, *229*, 109901. [CrossRef]
39. Bellia, L.; Błaszczak, U.; Diglio, F.; Fragliasso, F. Light-Environment Interactions and Integrative Lighting Design: Connecting Visual, Non-Visual and Energy Requirements in a Case Study Experiment. *Build. Environ.* **2024**, *253*, 111323. [CrossRef]
40. Bellia, L.; Pedace, A.; Barbato, G. Lighting in Educational Environments: An Example of a Complete Analysis of the Effects of Daylight and Electric Light on Occupants. *Build. Environ.* **2013**, *68*, 50–65. [CrossRef]
41. Gkaintatzi-Masouti, M.; van Duijnhoven, J.; Aarts, M.P.J. Simulations of Non-Image-Forming Effects of Light in Building Design: A Literature Review. *Light. Res. Technol.* **2023**, *55*, 669–689. [CrossRef]
42. Nazari, M.; Matusiak, B. Daylighting Simulation and Visualisation: Navigating Challenges in Accuracy and Validation. *Energy Build.* **2024**, *312*, 114188. [CrossRef]