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Analysis of Photopic and Melanopic Lighting in Teaching Environments

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Abstract: Daylight and lighting seem to be a key tool for people's well-being, however, there are no specific and agreed recommendations that address both photopic and melanopic aspects in educational environments. The present work analyzed melanopic light in four teaching environments considering photopic indoor lighting, daylight depending on the window orientation, location of the observer in the room, and their line of view. The façade direction, daylight at 11.00 a.m. for six months from October to March, and the characteristics of each classroom, such as reflectance of the surfaces, location of the luminaires and their spectral and spatial power distributions, or calculation points affecting the melanopic light reaching the corneal vertical plane of a hypothetical control observer were studied. For this evaluation, classrooms were experimentally treated and simulated using DialuxEvo software, and the computer-generated values resembled the experimental values. Once the study was performed, an improvement proposal, based on LED lighting, was made to optimize the classroom lighting considering the melanopic requirements, which we ensured that users who passed through these classrooms had an adequate amount light at any time of the day. Our results simplify to the greatest lighting projects and enable designers to carry out optimized evaluations of specific environments from both the photometric and circadian perspectives.

Keywords: daylight; circadian light; spectral power distribution; well-being; lighting projects; teaching environments

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1. Introduction

Light is a powerful stimulus that regulates and influences different physiological functions, such as the endocrine and behavioral systems, sleep-wake cycles, alertness and disruption of circadian rhythms [1,2]. Lighting in educational spaces needs specific designs to provide visual comfort and maintain concentration to perform tasks and stay awake and mentally fast [3–6]. This wellbeing is generally found with adequate daylight levels, which are dependent on seasonality, the orientation and windows in facades or the elevation of the sun on skydome [3,7,8]. To achieve these same characteristics, lighting is achieving high levels of specialization in controlling its spectral and spatial power distributions, intensity, duration or timing [9]. However, indoor lighting projects are also dependent on the reflectance of the walls, position of the furniture, the number of luminaires located in the ceiling and their spatial power distribution or the spectral power distribution (SPD) of the lamps [1,3,10,11].

These biological and behavioral effects of non-image forming effects of light, are influenced by a distinctive type of intrinsically photosensitive retinal ganglion cells (ipRGCs), which contain melanopsin in addition to the conventional visual pathway composed of rods and the three types of cones, S, M and L [12–16]. Current new light measurement and evaluation strategies that consider the complex inputs of visual and non-visual responses through the eye have been proposed [17–19]. Therefore, the extent a given architectural lighting replicates the biological effects of daylight, how lighting may be used to minimize the damaging effects of shift workers working for long periods of time under light while promoting alertness and safety or how academic success rate is related to the classroom lighting environment should be considered [3–5,20,21].

Based on current knowledge, studies of how lighting affects physiological functions may help in the choice of different types of lighting depending on the environment: during the day in teaching spaces or at work, and at night or before going to sleep at home. Lighting influences work, learning performance and the quality of people's sleep [2]. Lighting projects that consider the possible effects of light on people and optimize lighting to create the greatest possible well-being in the short, medium or very long term, are called human-centric lighting (HCL) projects. However, the growing number of these projects do not correspond to the importance that circadian light should have based on relevant studies, perhaps for several reasons: the absence of clear and specific regulations and metrics, the inertia of the manufacturer and the market, the current unacceptable costs, the lack of appropriate and properly characterized products and the lack of a sufficient number of trained technicians, product promotion managers or lighting designers [21,22]. The visual effects of light are based on the two classic types of photoreceptors, rods and cones, which have different sensitivities, connections to other retinal cells and distributions throughout the retina. Rods have very low spatial resolution but are very sensitive to light, especially at low levels or scotopic vision [23]. In contrast, cones are very effective at discriminating details but are much less sensitive to light and activate at high levels or in photopic vision [24].

The photopic illuminance, $E_{photopic}$, and its definition in photometry is calculated from the Expression (1), where $K_m = 683 l\ m/W$ and $V(\lambda)$ is the photopic spectral response of the eye [25].

$$E_{photopic} = K_m \int_{\lambda=380}^{780} SPD(\lambda)V(\lambda)d\lambda \quad (1)$$

In contrast, non-image forming effects of light are based on ipRGCs, which transmit signals via the optic nerve to the brain and control functions, such as pupillary light reflection (dilation and contraction of the pupil in response to changing light levels), coordination of head and eye movements for tasks, such as reading or watching sports, or the response of the circadian system [26]. For the circadian system, ipRGCs send neuronal signals to the central nervous system along a neurological pathway known as the retinohypothalamic tract [27]. ipRGCs have spectral sensitivity to various wavelengths of light, and their maximum spectral sensitivity is 460 nm. Recent papers suggest that S-cone photoreceptors are also involved in circadian phototransduction, and the visual pathway may be retro-feed by ipRGCs [26,28,29]. Since the discovery of ipRGCs, different spectra and action metrics have been proposed to estimate the potential melanopic contribution of lighting, including three exceptional approaches, one of which was provided by the International Commission of Eclariage (CIE) and is considered the standard of reference [30]. Another recommendation is based on proposals elaborated by the International WELL Building Institute (WELL) [31]. One of the latest recommendations and more expanded in the scientific community is described by Rea et al. [29], among others. The WELL [31] recommends as an approximation a parameter known as equivalent melanopic lux (EML), which is one of the five components (α-opic) described as a criterion for "circadian illumination design". It is calculated by the Expression (2), being $K_{melanopic,E} = 831.8 l\ m/_{melanopic,E}$ and $S_{mel}(\lambda)$ the melanopic spectral response of the eye.

$$EML = K_{melanopic,E} \int_{\lambda=380}^{780} SPD(\lambda)S_{mel}(\lambda)d\lambda \quad (2)$$

The CIE standard stipulated the parameter melanopic illuminance equivalent (EDI) to daylight (D_{65}), defined as a D_{65}-type light source, which uses photopic illuminance $E_{photopic\ D65}$ to provide the same melanopic irradiation as a light source with SPD and photopic illuminance $E_{photopic\ SPD}$ [30]. This parameter is calculated with the Expression (3), with the constant parameter $K_{melanopic,D65} = 753.81\ m/W_{melanopic,D65}$.

$$\text{EDI} = K_{\text{melanopic,D65}} \int_{\lambda=380}^{780} \text{SPD}(\lambda)\ S_{\text{mel}}(\lambda) d\lambda \tag{3}$$

These two factors are related by the Expression (4) EML = 1.104 EDI. EML is also related to photopic illuminance by the Expression (5) and EDI by the Expression (6):

$$\text{EML} = 1.104\text{EDI} \tag{4}$$

$$\text{EML} = 1.218\ \frac{\int_{\lambda=380}^{780} \text{SPD}(\lambda)\ S_{\text{mel}}(\lambda) d\lambda}{\int_{\lambda=380}^{780} \text{SPD}(\lambda) V(\lambda) d\lambda}\ E_{\text{photopic}} = 1.218\ \text{MAF}\ E_{\text{photopic}} \tag{5}$$

$$\text{EDI} = 1.104\ \text{MAF}\ E_{\text{photopic}} \tag{6}$$

MAF is defined as the ratio between melanopic and photopic irradiance [32]. Based on these interrelationships, illuminance measured using a traditional luxmeter allows us to confirm photopic levels of light according to normative specifications, and melanopic contributions in melanopic lux (m-lux) may be easily evaluated according to the CIE standard and from the WELL perspective based on the known SPD of the light.

Evaluation of lighting quality in educational buildings reveals serious lacks in illuminance levels of photopic light related to the visual tasks [33,34], it has described that adequate combination of artificial lighting and daylight seems to generate visual comfort and positive predisposition to learn in these areas [35,36]. Although many authors have described these situations, lighting involves non-visual effects that should be measured and analyzed simultaneously with the visual ones. Our method solves this gap, we describe an innovative way to address both issues knowing photopic illuminances and SPDs of the light reaching a plane. This methodology provides important keys to lighting designers, without complex calculations founded in the revised bibliography, to develop architectural projects or scientific studies irrespective of the circadian metric, due to EDI and EML are related as it has previously described. Standards (CIE) and recommended practices (WELL) provide theoretical background needed to understand human behavior but it is difficult to find a practical, simple and realistic method that enable designers to develop lighting projects.

With the time spent in classrooms, young people are exposed to high amounts of artificial lighting every day and daylight can be an important part of the indoor environment: its spectral contribution, dependence with the window orientations, or location of the sun in the skydome. The current paper analyzed the lighting of four classrooms located in buildings in Zaragoza (Spain) that are used for educational activities. The procedure was divided into two parts. (1) Four classrooms with windows with different orientations were selected to assess the daylight illumination over six months. Experimental measurements were performed at several points in each room with indoor lighting and daylighting. The parameters measured were photopic illuminance and SPD at horizontal and three vertical planes. From these results, melanopic contributions were calculated according to the CIE standard and WELL recommendations in m-lux. (2) Simulated spaces with DialuxEvo were constructed from the real dimensions and characteristics of each classroom, including their façade orientations and the different luminaires located in their ceilings. An optimized indoor lighting proposal of each classroom was presented, which showed that our methodology may be easily extrapolated to any lighting project that considers photopic and melanopic contributions.

2. Materials and Methods

2.1. Characteristics of the Teaching Classrooms and Measured Modes

Four classrooms located in teaching buildings in Zaragoza (Spain) were selected for realistic evaluations. Their urban design had to accomplish the absence of obstructions near the windows of the building and approximately orthogonal façade orientations to guarantee proper daylighting at all the points of evaluation. The following spaces were selected: Classroom 1 was a 9.00 × 7.00 × 2.75 m (long × wide × high) computer classroom with a south-east orientation (135° from north); Classroom 2 was a 5.70 × 4.60 × 2.60 m library or meeting room with a north-west orientation (315° from north); Classroom 3, was an 8.50 × 5.65 × 2.82 m teaching classroom with a south-west orientation (225° from north); and Classroom 4, was an 8.00 × 3.90 × 3.03 m teaching classroom with a north-east orientation (45° from north) (Figure 1).

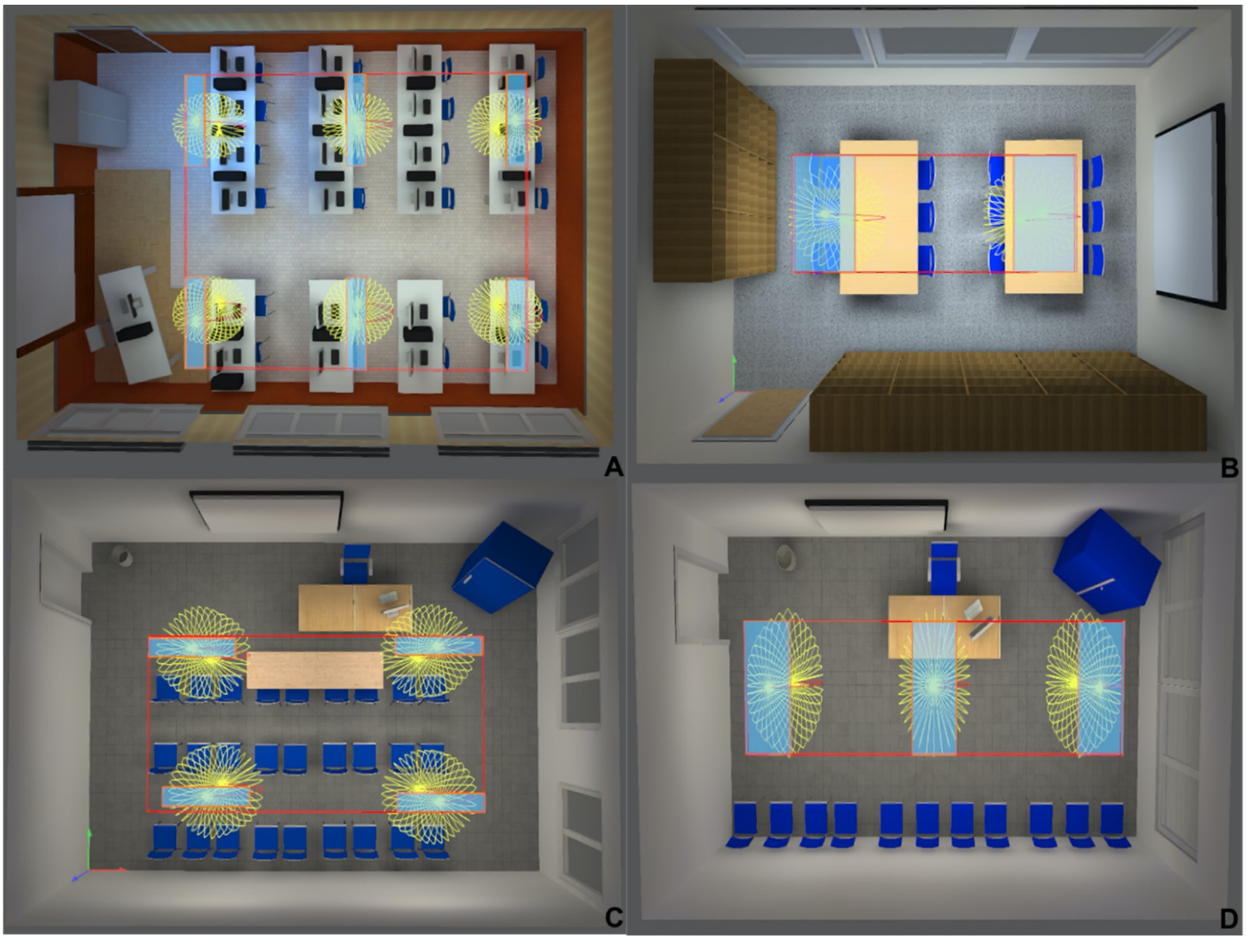


Figure 1. Simulated classrooms by DialuxEvo. (**A**) Classroom 1; (**B**) Classroom 2; (**C**) Classroom 3; (**D**) Classroom 4.

The choice of the number of experimental measurement points for each classroom was based on the layout of each teaching space and covered the space where users should be positioned. A 3 × 3 grid (9 points) was chosen in Classrooms 1 and 2 because they were more square-shaped classrooms. Therefore, a 3 × 2 (6 points) grid was made for Classrooms 3 and 4 because these classrooms were narrow and elongated. These points were located at a distance from each other to cover as much useful space as possible, i.e., where the desks are located (Figure 1). Furniture, walls, windows and ceiling of each classroom were simulated taking into account their distribution, relative position and materials of each surface.

As previously mentioned, the experimental measurements corresponding to the first part of the study were performed using a calibrated spectroradiometer (model Avaspec-1024, Avantes, Apeldoorn, The Netherlands, with NPL E01110063/DDK calibration and NIST traceability). It was used for analyzing SPD in irradiance (μW/cm^2) mode from 380 nm to 780 nm and connected to a computer. Photopic illuminance (lux) was also measured, and circadian parameters under CIE S 026/E:2018 [30] and WELL Feature 54 [31] regulations were calculated, following respective methods. At each defined point, a measurement was taken 80 cm from the ground by placing the spectroradiometer on the horizontal plane so that the lighting from the ceiling reached it, which simulated the light that reached the desk plane. At each point, the spectrophotometer was placed at a height of 1.30 m to simulate the corneal plane. The device was oriented toward the blackboard (0°), then at 45° between the window and the blackboard and finally toward the window (90°) to simulate a real dynamic observer with the ability to rotate his corneal plane around a vertical axis, i.e., a subject who rotates his neck (Figure 2).

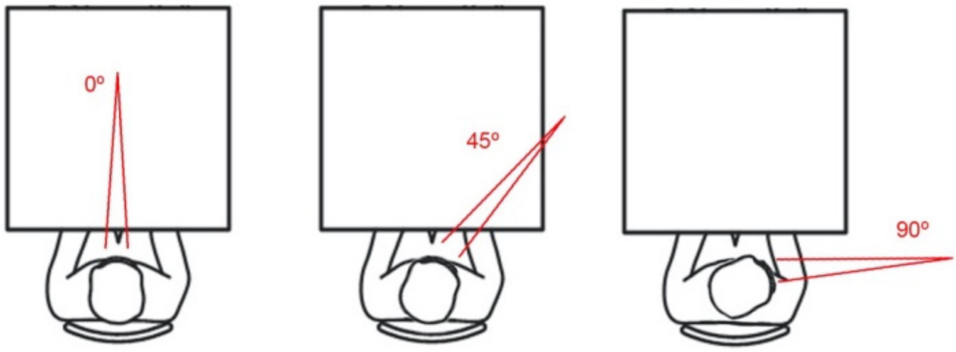


Figure 2. Eyes orientation at a height of 130 cm. On the left, the subject is looking straight at the blackboard and it is considered 0°; in the middle, the subject is turning the head 45° with respect to the blackboard and on the right looking 90° with respect to the blackboard, to the window.

The luminaires corresponding to each classroom had different dimensions and photometric characteristics (Table 1, Figure 3). The measurements were performed exclusively at these points throughout the six months that the experiment lasted. Depending on the luminaire spatial location and the viewing angle, the illumination reaching the corneal plane changes.

Table 1. Number of luminaires, number of fluorescent tubes and characteristics of the luminaires selected in DialuxEvo of each one by classroom.

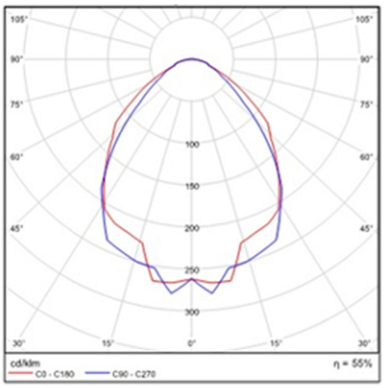
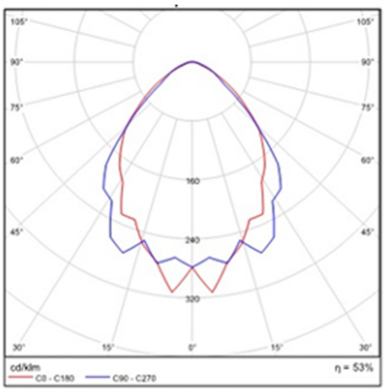
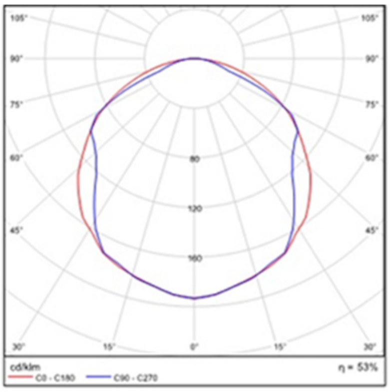
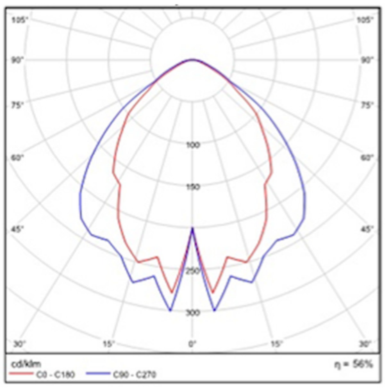
Classroom# Number of Luminaires/Tubes	Spatial Power Distribution	Classroom# Number of Luminaires/Tubes	Spatial Power Distribution
#1 6/2		#2 2/4	

Table 1. *Cont.*

Classroom# Number of Luminaires/Tubes	Spatial Power Distribution	Classroom# Number of Luminaires/Tubes	Spatial Power Distribution
#3 4/2		#4 3/3	

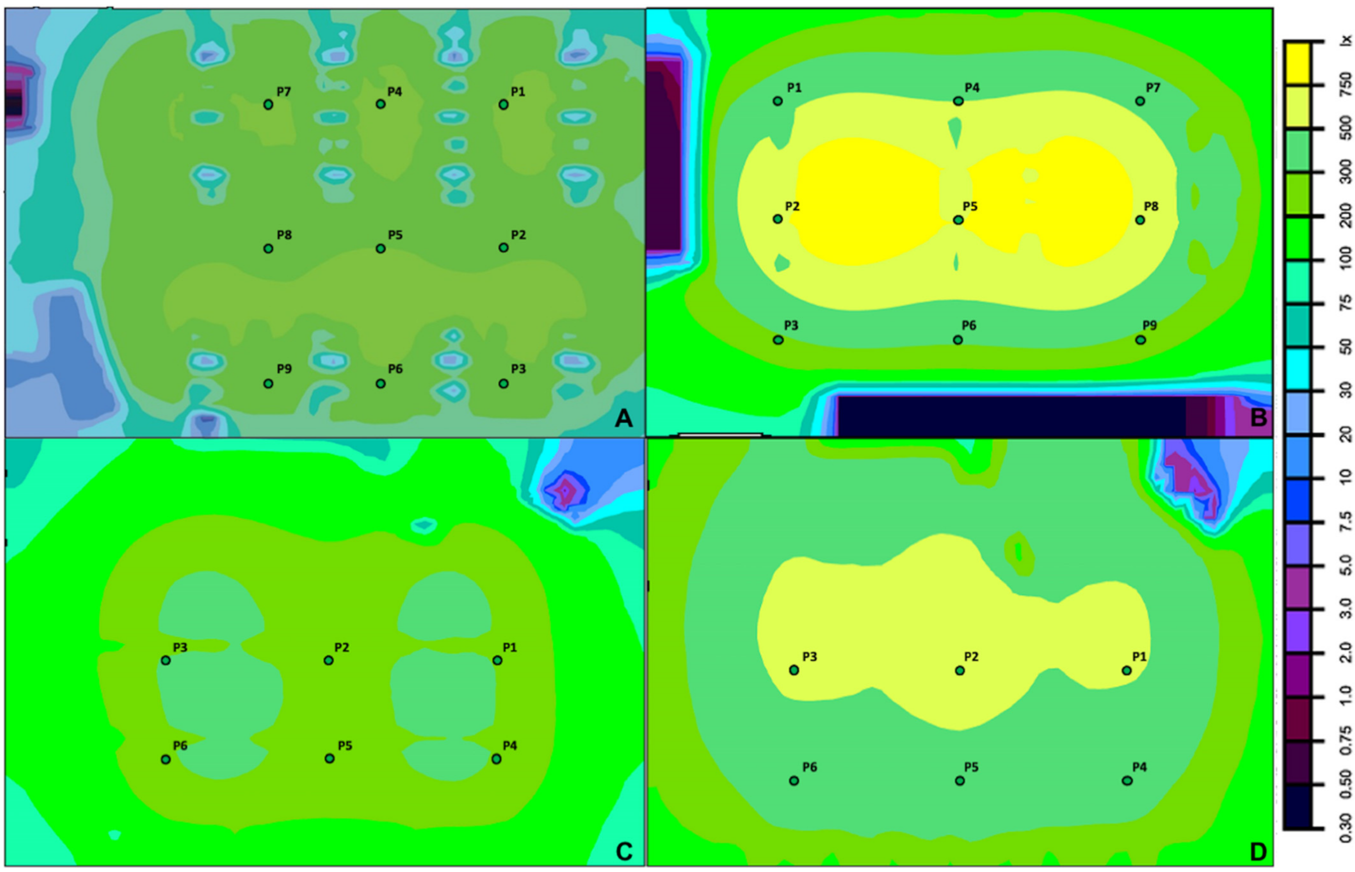


Figure 3. Photopic illuminance (lux) in false color at the horizontal plane (height 0.80 m from the floor). (**A**) Classroom 1; (**B**) Classroom 2; (**C**) Classroom 3; (**D**) Classroom 4 and measurement number points for each classroom.

2.2. *Simulated Measurements*

The classroom simulations, calculation and visualization of the lighting project in photopic terms were performed using the DialuxEvo program. The classrooms were simulated with their real dimensions and characteristics, and the color, texture and degree of reflections of the object, wall, floor and ceiling were modified so that the simulation of each classroom was as real as possible. The same points were located where experimental measurements were taken to perform the simulated calculations (Figure 1). Table 2 shows the experimentally measured characteristics of the simulated classroom environments.

Table 2. Classroom characteristics: reflection factor and reflective coating.

Classroom #	Walls	Floor	Ceiling
1	Lower half 12–0/upper half 70–0	75–1%	90–0
2	85–0	35–10%	85–0
3	82–0	22–4%	75–0
4	90–0	22–4%	90–0

The characteristics of the luminaires selected in the DialuxEvo program catalogs were also indicated, with similar characteristics as the luminaires that were installed in classrooms. Table 1 shows the chosen luminaires for each classroom. Once the classrooms were simulated, the calculation points were placed with the appropriate orientations. The CIE 2019 [30] declaration reinforces the idea that the metric of choice to quantify how polychromatic light affects different situations of daily life is the melanopic EDI. Bright days help maintain the circadian rhythm and promote sleep at night [37], such as high melanopic EDI and evenings and nights as low melanopic EDI.

3. Results and Discussion

3.1. Photopic Indoor Lighting

The collected photopic illumination values from the experimental and simulated measurements were shown, considering only light provided from luminaires. The European regulation of lighting for indoors, standard UNE 12464.1 [38], establishes minimum values to consider correct lighting in teaching environments (Table 3).

Table 3. Minimum levels of photopic illumination according to UNE 12464–1 [38], min = Eminimum, Eave = Eaverage.

Indoor Type	Emin (lux)	UGR_L	Uo = Emin/Eave	CRI
Classroom for diurnal/nocturnal classes	300/500	19	0.6	80
Computer rooms	300	19	0.6	80
Meeting rooms	200	22	0.4	80
Library with shelves/reading rooms	200/500	19	0.6	80

Simulated values of photopic illuminances 80 cm from the floor were matched to the measured values (Figure 3); Classroom 1, average was 129 lux, with a maximum value of 266 lux; Classroom 2, average was 358 lux, with a maximum value of 950 lux; Classroom 3 average was 192 lux, with a maximum value of 350 lux; and Classroom 4 average: 361 lux, with a maximum value of 601 lux. These results showed that values of Uo were hardly feasible in none of the classrooms.

Vertical photopic illuminance values at 130 cm from the floor, depending on the orientation of Figure 2 (0°/45°/90°) in each classroom and at each point with artificial light, are summarized in Table 4.

The experimental horizontal values measured in Classroom 1 did not reach the minimum established by standards. In Classroom 2, it has been verified that in the horizontal plane the minimum requirements are reached plane, but highly variable illuminance levels at the corneal plane illuminances were measured from one point to another. The values collected with artificial light from Classroom 3, which was dedicated to teaching and holding meetings, did not meet current regulatory requirements because the value of 300 lux was exceeded at only one point (P4, 344 lux). The values collected from Classroom 4, which was dedicated to the same purposes as Classroom 3, reached levels of 300 lux, which was also reached in two of the six points of the corneal plane of an observer looking at the blackboard. Notably, Classrooms 2 and 4 were the best artificially lit, but they hardly achieved the values required by standards. There was no general uniformity in the values because there was more than a 30% difference between the point with the greatest illumination and the point with the lowest value, except for Classrooms 3 and 4, which in the corneal plane of an observer looking at the blackboard does there is uniformity.

Table 4. Vertical photopic illuminance (lux) simulation the position of the corneal plane (height 1.30 m from the floor). The 0° orientation is in blackboard direction, 45° and 90° from 0° rotating to the windows location for each classroom.

	Classroom 1			**Classroom 2**			**Classroom 3**			**Classroom 4**		
	0°	**45°**	**90°**	**0°**	**45°**	**90°**	**0°**	**45°**	**90°**	**0°**	**45°**	**90°**
P1	84.7	86.8	100	307	102	54.5	147	70.2	42.3	201	108	62.8
P2	89.4	94.5	120	524	491	242	123	123	145	255	230	168
P3	62.8	39.9	26.3	158	273	242	165	177	156	237	231	179
P4	102	119	115	244	117	78.8	125	74.8	47.8	283	167	67.7
P5	88.6	131	138	384	340	251	124	131	135	335	264	138
P6	56.1	35.9	28	138	220	281	160	208	168	325	276	154
P7	122	114	86.1	90.5	78.0	73.8						
P8	94.3	100	103	98.5	140	314						
P9	68.6	30.7	23.9	58.2	168	292						

3.2. Melanopic Lighting from Artificial Lighting and Daylight

The CIE 2019 [30] and WELL Building Standard [31] recommend minimum levels of melanopic light at the corneal plane from 150 m-lux to 250 m-lux depending on the functions of the room. In teaching rooms, higher melanopic output can improve concentration, reading comprehension, and reducing sleepiness during afternoon cognitive tasks [39]. The most critical levels to achieve this minimum are measured only with indoor lighting from the luminaires evaluated because daylight provides high levels of melanopic light [8]. These experimental results are shown in Table 5.

Table 5. Melanopic illumination (m-lux) in the corneal plane, only artificial light (vertical at 130 cm 0°: board).

	Classroom 1		**Classroom 2**		**Classroom 3**		**Classroom 4**	
	EML	**EDI**	**EML**	**EDI**	**EML**	**EDI**	**EML**	**EDI**
P1	73.69	66.74	71.60	64.85	90.88	82.31	126.25	114.35
P2	73.07	66.18	88.01	79.71	84.66	76.68	135.13	122.39
P3	53.66	48.60	57.78	52.33	101.25	91.70	143.13	129.63
P4	65.91	59.69	217.56	197.05	92.18	83.49	154.81	140.21
P5	68.63	62.15	213.78	193.62	83.02	75.19	165.41	149.82
P6	46.99	42.56	120.42	109.07	100.00	90.57	164.86	149.32
P7	68.30	61.86	81.27	73.61				
P8	59.10	53.53	95.75	86.72				
P9	49.51	44.84	73.43	66.51				

The vertical EDI reaching the corneal plane at each location varied considerably. Without loss of generality, the discussion below may be performed the same as EML recommendations because both parameters are related by the expression EML = 1.104EDI. In general, very low levels of melanopic light were measured in the four rooms considering that they have educational purposes from 9.00 a.m. to 9.00 p.m., every day from September to July. It is obvious that daylight plays an important role in indoor lighting, as the results show. The amount of melanopic light received at each position, considering only daylight or evaluating indoor lighting plus daylight, changed over the six months that were assessed in this study. For simplicity, the maximum and minimum values of melanopic illuminance were analyzed in each case, being the rest of the results intermediate values, as shown in Figures 4–7. Under these conditions and in terms of EDI values, P6–45° in Classroom 1, which was located next to the window, received up to 66,743 m-lux in March, and it only reached 51 m-lux at P7–0° in December; the SPD also changed. Daylight in the first P6 had 5002 K, and P7 had a colder CCT with 5519 K. The CRI was over 95 in both cases, which is considered adequate to perform academic tasks [38]. Taking into account artificial lighting in addition to the previously evaluated daylight, the results changed considerably in location and melanopic levels of light, orientation, month and SPDs. P6–90° reached 65,068 m-lux in November, and P7–0° reached 115 m-lux in December, which increased due to the position of this point below one luminaire. The photometric spectra reaching P6–90° corresponded to daylight with 5343K and CRI 99, and important differences were found in P7–0°, where the SPD of the fluorescents with 4287 K and CRI 88, predominated.

Classroom 2 was also analyzed in terms of maximum and minimum values. Daylight P4–90° in October varied from 3057 m-lux to P6–90° in December 89 m-lux, which corresponded to 5577 K and 7960 K, respectively, and CRI 98–99. Daylight combined with indoor lighting changed and reached higher values at P4–90° in October of 2982 m-lux; 7921 K, CRI 98 and lower values at P3–0° in December 180 m-lux, 5742 K, CRI 99. Indoor lighting in this space did not contribute to spectrally modifying the SPD of the daylight coming through the windows, and luminaires in this area had the least influence.

Measurements in Classroom 3 provided daylight levels of 2486 m-lux at P1–90° in March with 6721 K and 48 m-lux at P3–0° in January with 5608 K; CRI 99 in both cases. When daylight was combined with indoor lighting, P1–0° in March had 2589 m-lux; 6623 K, CRI 98 and P6–0° in January 155 m-lux, 4074 K, CRI 88; in this last case, the SPD measured is mainly due to the fluorescent located on the ceiling over the control point.

The last evaluated space was the Classroom 4; daylight reached at P1–90° in March 2733 m-lux, 6729 K and P3–0° in December 34 m-lux, 5452 K; in both cases CRI was 99. Daylight combined with indoor lighting showed at P1-90° in March 2807 m-lux; 6442 K, CRI 98 and at P3–0° in December 134 m-lux, 3714 K, CRI 86; in this circumstance, the SPD is mainly due to the fluorescent located on the ceiling over the point of measurement as happened in Classroom 3.

Globally, it can be observed that depending on the month of the year and position of the sun in the skydome, daylight photopic illuminances and CCTs had highly variability with both irradiance and the SPD reaching the control points, in consequence, location of the evaluated point in the space and the orientation of the vertical plane (0°/45°/90°) is critical when melanopic illuminance are calculated. Moreover, when indoor lighting is considered simultaneously with daylight, important changes are observed correlated to the enumerated items and consequence of the spectral irradiance in each case. With the exposed results, it could be thought that lower CCTs provided high levels of melanopic illuminance but these values are due to the amount of photopic illuminance reaching the corneal plane in each case. In all cases, it can be observed CRIs over 80 that can be correct in relation to the academic tasks that are carried out in these rooms, according to Table 3.

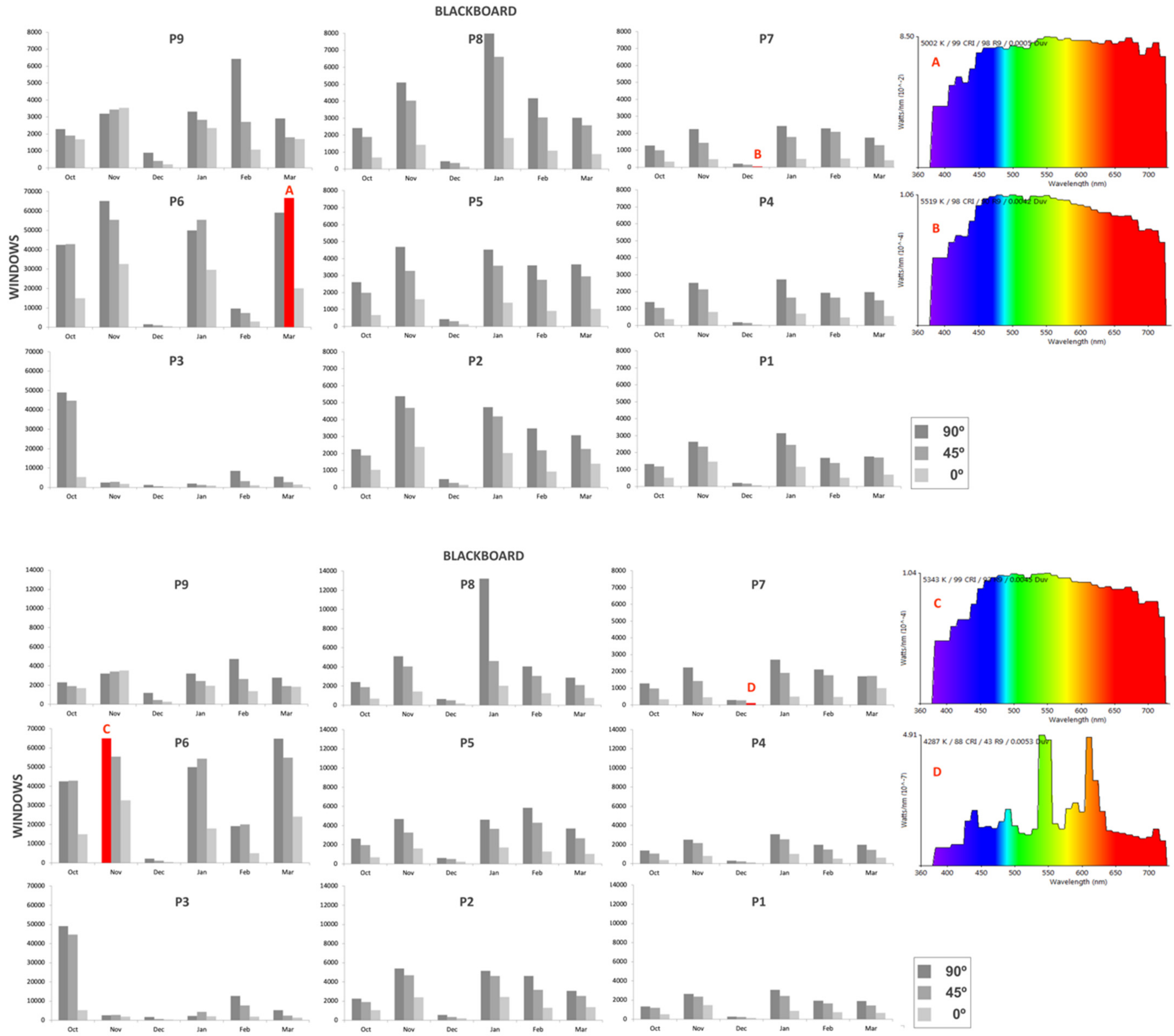


Figure 4. Classroom 1. Melanopic values according to the CIE standard (EDI melanopic lux) acting, in upper figure daylighting in Classroom 1 at each point (P1, P2, P3, P4, P5, P6, P7, P8 and P9) and in the three gaze orientations (0°, 45° and 90°); in lower figure, daylighting + artificial lighting in Classroom 1 at each point (P1, P2, P3, P4, P5, P6, P7, P8 and P9) and in the three gaze orientations (0°, 45° and 90°). Right figures, SPD of (**A**) maximum daylighting in the month of March at Point 6 with 45° orientation; (**B**) minimum daylighting in December at Point 7 with orientation at 0°; (**C**) maximum daylighting + artificial lighting in the month of November at Point 6 with 90° orientation; (**D**) minimum daylighting + artificial lighting in the month of December at Point 7 with orientation at 0°. OsramColorCalculator was used to plot the SPDs.

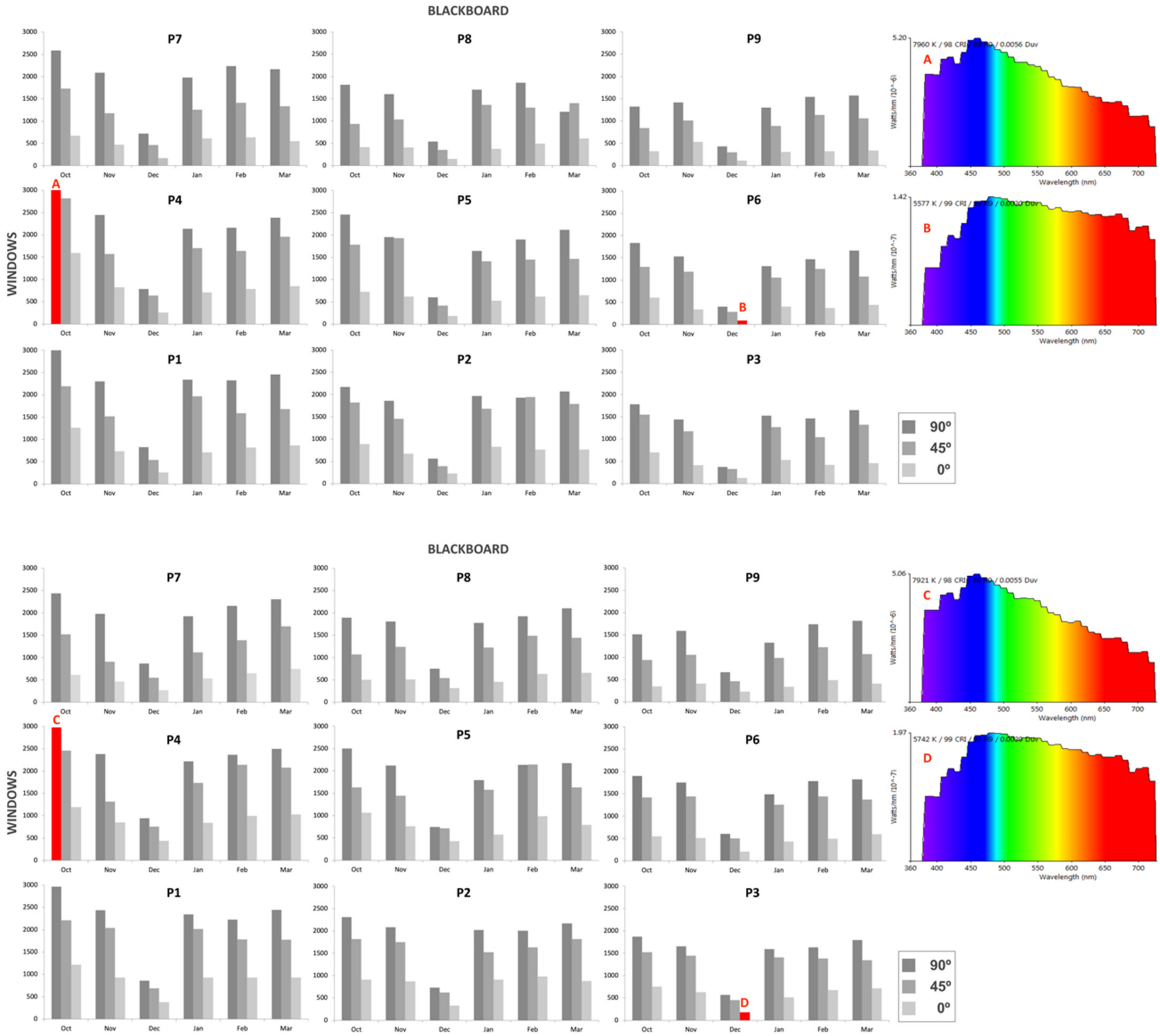


Figure 5. Classroom 2. Melanopic values according to the CIE standard (EDI melanopic lux) acting, in upper figure daylighting in Classroom 2 at each point (P1, P2, P3, P4, P5, P6, P7, P8 and P9) and in the three gaze orientations (0°, 45° and 90°); in lower figure, daylighting + artificial lighting in Classroom 2 at each point (P1, P2, P3, P4, P5, P6, P7, P8 and P9) and in the three gaze orientations (0°, 45° and 90°). Right figures, SPD of (**A**) maximum daylighting in the month of October at Point 4 with 90° orientation; (**B**) minimum daylighting in December at Point 6 with orientation at 0°; (**C**) maximum daylighting + artificial lighting in the month of October at Point 4 with 90° orientation; (**D**) minimum daylighting + artificial lighting in the month of December at Point 3 with orientation at 0°. OsramColorCalculator was used to plot the SPDs.

Orientation of the windows is crucial in this experiment; Classroom 1 is facing south-east; at 11.00 a.m. the sun is by this position in the skydome reaching photopic vertical illuminance levels up to 70,000 lux in points by the windows. Classroom 2 was north-west, it had the higher measured CCTs and the least variation between the extreme melanopic illuminance values measured, irrespective of the indoor lighting which had insignificant influences. Classroom 3, south-west, and Classroom 4, north-east, were the worst subjectively illuminated and results shows high variability.

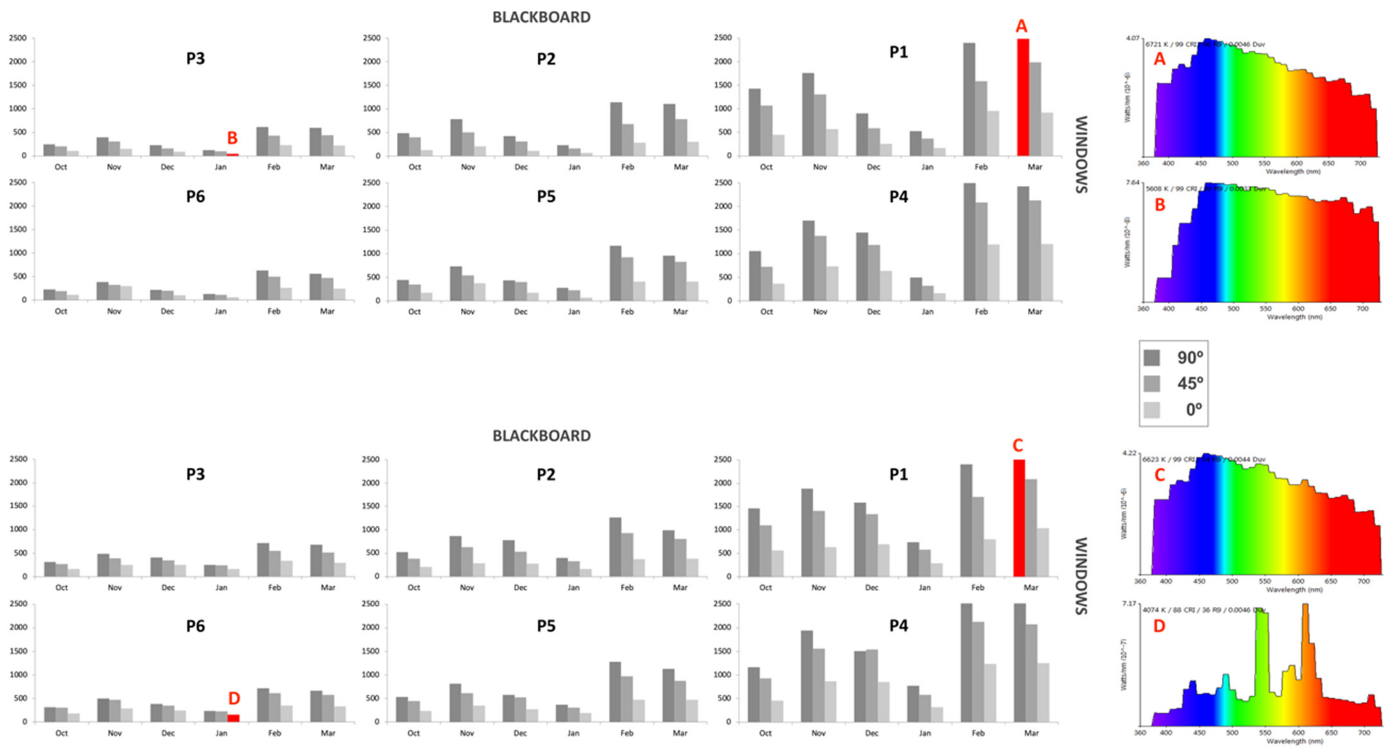


Figure 6. Classroom 3. Melanopic values according to the CIE standard (EDI melanopic lux) acting, in upper figure daylighting in Classroom 3 at each point (P1, P2, P3, P4, P5 and P6) and in the three gaze orientations (0°, 45° and 90°); in lower figure, daylighting + artificial lighting in Classroom 3 at each point (P1, P2, P3, P4, P5 and P6) and in the three gaze orientations (0°, 45° and 90°). Right figures, SPD of (**A**) maximum daylighting in the month of March at Point 1 with 90° orientation; (**B**) minimum daylighting in January at Point 3 with orientation at 0°; (**C**) maximum daylighting + artificial lighting in the month of March at Point 1 with 90° orientation; (**D**) minimum daylighting + artificial lighting in the month of January at Point 6 with orientation at 0°. OsramColorCalculator was used to plot the SPDs.

A healthy circadian lighting profile consists of a sufficient light stimulus during the day and a low level of light exposure during the night hours, and daylight from the sun is optimal for this purpose because it provides high levels of stimuli in the morning and decreases throughout the day. Exposure to higher illuminance levels of light, artificial or daylight, during earlier hours of the morning could improve non-visual effects of light. In our study only 11.00 a.m. was selected to evaluate these effects; considering that 250 m-lux should be maintained during daytime school, a more comprehensive study could be needed to evaluate how daylight changes over the entire day [40]. The daily dose of light received by people in industrialized countries may be too low because people spend much of their time in spaces that do not allow sufficient window access to provide enough daylight [41]. Positive effects of daylight were described [20,42] in contrast to working spaces without windows that seem to affect the well-being of workers compared to open offices [43]. The effect of lighting on the circadian rhythm is greater in children and adolescents than adults, which highlights the importance of analyzing lighting in educational spaces [3]. Safranek et al. [44] also commented that designing buildings to take full advantage of daylight may be a strategy to reduce the energy consumption of electric lighting and the operating costs of educational centers. On the other hand, Ahmed et al. [45] performed daylighting simulation at various window transparency levels, looking for an optimal artificial lighting load for an Egyptian office building. The technical and economic parameters of each alternative were simulated and the overall systems performances were evaluated. This effort leads to added complexity in the lighting control design and programming process and in simulation methods. The determination of the SPD of daylight is complex and was reflected in the variability of the availability of daylight during the different months of measurements in our study, which always occurred at the same time. The importance of the sky conditions [8] at the measurement moment and the glazing of the windows should be noted. Figueiro et al. [20] noted that it was difficult to achieve enough circadian light at the corneal level in employees working in five different buildings, although four of the buildings were designed to maximize daylight, and the authors highlighted the need to consider office furniture locations and window shades for greater visual comfort of the occupant. The variability of our results in architectural lighting, including daylight, could impact student non-visual tasks. We showed differences in classroom lighting, in luminaires and lamps and among locations in a specific room, including season of the year or line of view. Lighting with a short-wavelength spectrum improved reading fluency performance [46], concentration [47] and cognitive processing speed [48]. Lighting that varies in CCT and illuminance increased the attention and reading speed of elementary and high school students [49] and the performance of different tasks in nursing homes [50]. Lighting has been evaluated in these terms in contexts other than academia, and there is evidence of the influence of high CCT on improving fatigue, alertness, daytime sleepiness, and work routines [51] and on alertness, mood, daytime sleepiness, evening fatigue, and work tasks [52,53].

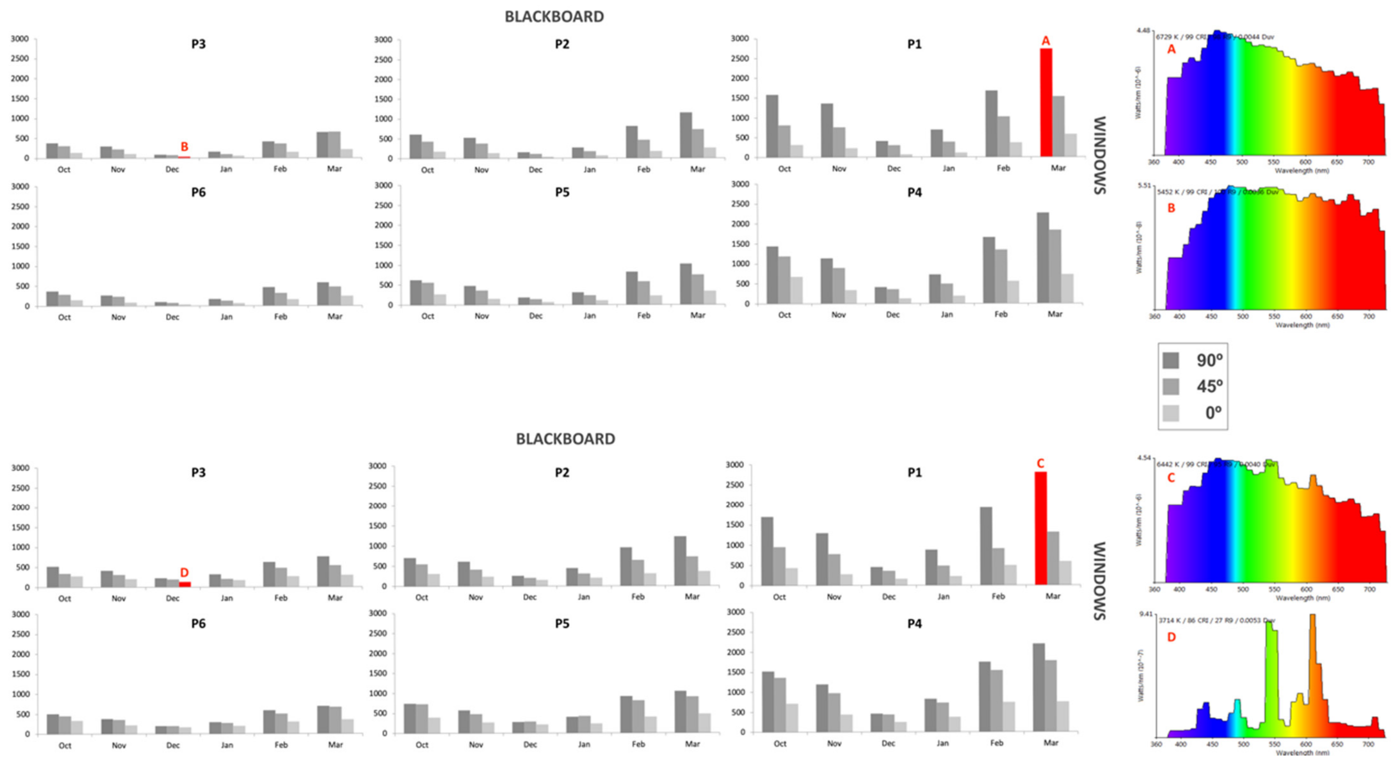


Figure 7. Classroom 4. Melanopic values according to the CIE standard (EDI melanopic lux) acting, in upper figure daylighting in Classroom 4 at each point (P1, P2, P3, P4, P5 and P6) and in the three gaze orientations (0°, 45° and 90°); in lower figure, daylighting + artificial lighting in Classroom 4 at each point (P1, P2, P3, P4, P5 and P6) and in the three gaze orientations (0°, 45° and 90°). Right figures, SPD of (**A**) maximum daylighting in the month of March at Point 1 with 90° orientation; (**B**) minimum daylighting in December at Point 3 with orientation at 0°; (**C**) maximum daylighting + artificial lighting in the month of March at Point 1 with 90° orientation; (**D**) minimum daylighting + artificial lighting in the month of December at Point 3 with orientation at 0°. OsramColorCalculator was used to plot the SPDs.

3.3. Optimization of Artificial Lighting

Based on previous results, an easy method of optimization of artificial lighting was created to accomplish photopic and melanopic requirements. First, the number or luminous flux of the tubes can be increased in simulated classrooms to achieve minimum illuminance values in the horizontal plane according to their normative requirements and in the vertical plane from 150 to 250 m-lux. There are different ways to improve the proposed HCL requirements. The most important way to improve illumination is changing the type of lamp, the degree of reflection of the surfaces, the photometric characteristics, its distribution, etc. Ideally, a dimmable luminaire can change the SPD and CCT to change the circadian stimulus throughout the day, which can serve as a complement to daylight to promote image forming and non-forming achievements every day. These changes optimize the well-being of the individual and behavioral responses that affect circadian regulation. Light-emitting diodes (LEDs) are a good solution for this problem because their spectrum is continuous and can be made to resemble or complete sunlight to contribute significantly to melanopic lighting. As described in the introduction section, melanopic light is related to photopic illuminance reaching the corneal plane by the expression EDI = 1.104 MAF $E_{photopic}$ and EML = 1.104 EDI = 1.128MAF $E_{photopic}$. Since $E_{photopic}$ can be experimentally measured and simulated with DialuxEvo, controlling this magnitude $E_{photopic}$ at the points of interest can easily achieve, artificial indoor melanopic light. This section shows how it may be achieved with four proposed LEDs with different SPDs and CCTs (Figure 8 and Table 6). According to current circadian metric models, it is important to increase the intensity of the lighting stimulus and the short wavelength spectral content during the day, particularly in spaces without daylight. We showed that all required levels of melanopic illuminance may be achieved with every LED, but lower CCTs require higher photopic illuminance to reach the specified amounts of melanopic light. One shortcoming of this situation was that a higher consumption of energy was required by the electrical installation to provide such high levels of melanopic light at a hypothetical corneal plane and that horizontal photopic illuminance could exceed rates that do not lead to accomplishment with the normative specifications collected in UNE 12464.1.

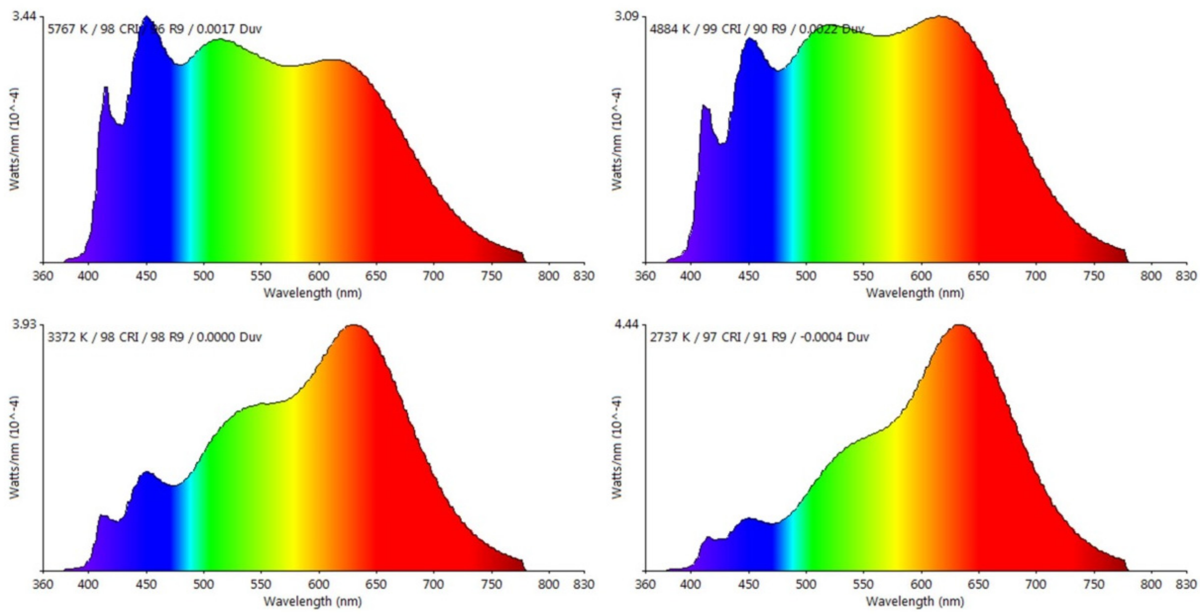


Figure 8. Spectral power distribution corresponding to the four selected LEDs. OsramColorCalculator was used to plot the SPDs.

Table 6. Photopic illuminance at the corneal level needed to provide 250–150 m-lux with four LEDs.

	5771K/98CRI	**4884K/99CRI**	**3373K/98CRI**	**2737K/97CRI**
MAF	0.846	0.752	0.535	0.416
EDI		Ephotopic		
250	268	302	424	545
150	161	181	254	327

Although calculations are simple, there is no consensus on the lighting requirements to achieve possible non-image forming effect of lighting effects on occupants because they can serve as calculation guidelines. It is difficult to understand effective implementation [44] and how the metrics apply to a realistic teaching space because the design recommendations are in transition. For example, the WELL Education Pilot [31] suggests that EML > 125 m-lux for 4 h a day is an appropriate stimulus in an educational setting. However, the Collaborative for High Performance School (CHPS) Core Criteria 3.0 [54] suggests that twice that amount is needed (EML > 250 m-lux). These variations make it difficult for installers or designers to follow guidelines, and it does not help save energy. It is recommended to reduce light levels and short wavelength spectral content in the evening and at night for healthy sleep, due to at the same photopic illuminance level, and lower rates of EDI will be present as shown in Table 6. The relative importance of increasing daylight levels relative to reducing nightlight levels in realistic environments is not known. If reducing light levels and limiting short wavelength content at night is more effective, greater energy savings may be achieved, and daytime light levels would not need to be increased. Additional research is needed to optimize lighting energy use to achieve the effective stimulus characteristics and exposure times required for circadian health and develop lighting projects based on photometric quantities. A solution could obtain the relationship between day-night exposure ranks and the relative result, and energy savings may be achieved by reducing nocturnal light values rather than significantly increasing day light amounts. The compromises between design recommendations and energy efficiency objectives cannot be fully expressed until circadian strategies and an agreed supply of light stimuli have been fully settled in lifelike locations with identifiable healthy properties and wellness benefits.

4. Conclusions

The methodology of this research was based on experimental measurements in four concrete classrooms to assess indoor lighting and the impact on daylight over six months under photopic and melanopic illumination at the working plane and corneal level in specific positions distributed in each classroom. Therefore, this paper checked whether the analyzed spaces complied with the photopic regulations and melanopic recommendations established by the International Commission on Illumination (CIE) when exclusively artificial light was present and when daylight and artificial light acted together. The impact of circadian illumination is directly related to the SPD characteristics of incident light on the cornea, and the illumination at the horizontal working plane is not directly relevant. Because photopic and melanopic illuminances are related by the MAF factor, indoor lighting may be improved by varying the SPD and photopic illuminance levels to complement daylight contributions based on month and façade orientation while considering dimmable luminaires as the best solution to promote well-being and save electrical consumption. This study provides background information for developing lighting projects from a global perspective and provides clues and a method to transform traditional lights into well-being lights. However, further studies focused on the influence of the spectral reflectance of the surfaces or more profound knowledge of subjective behavior in addition to optimal conditions for performing visual tasks are needed to assess healthy and comfortable real-life environments.

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