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Impact of Daylighting on Visual Comfort and on the Biological Clock for Teleworkers in Residential Buildings

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Abstract: The current socio-economic scenario has promoted telecommuting at home for a significant number of workers, mainly due to the sanitary situation experienced and the improvement in communication technologies. However, the work context at home is often not suitable for teleworking since the environmental conditions are not usually adequate for good performance and the wellness of workers. The received light, both in quantity and in spectrum, affects the visual comfort and performance of the worker through the regulation of the circadian stimulus. Accordingly, the objective of the present study is to ascertain the influence of natural daylight on the performance and health of teleworkers, considering a room at home analyzed in three different locations, two orientations, two-time schedules, and two window shapes. The impact of natural light on health was assessed using the Circadian Stimulus Autonomy (CSA) produced by daylight during the morning, while the illuminance requirement was defined in accordance with the Daylight Autonomy (DA). The results obtained were contrasted with a real test cell under real daylight conditions. The conclusions of this study serve to determine the suitable windowed areas of the analyzed room where teleworkers obtain the appropriate lighting performance and well-being.

Keywords: daylighting; teleworking; visual comfort; circadian stimulus; daylight autonomy

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1. Introduction

1.1. Background

Nowadays, thanks to the extensive proliferation of information technology devices—laptops, tablets, smartphones—and the advancement of telecommunication systems, numerous tertiary work activities can be performed remotely. Technology gets people free to organize work-life smartly and dynamically, and homeworking is by now a widely spread phenomenon.

Contrary to what one might imagine, the homeworking concept is not a new-born concept. The words "telecommunicating" and "telework", describing the possibility of working in places different from the standard offices, were introduced by Jack Nilles in 1976, and the phenomenon started to spread in the United States in the 80s [1]. Then, it expanded all over the world and in Europe as well [2]. Surely, the COVID-19 pandemic boosted its diffusion. Indeed, suddenly, due to physical distancing needs, mandated lockdowns, and travel restrictions, as well as the closure of offices and schools, working from home became the only option for many people. According to Eurofound [3], the percentage of European workers who started to do their jobs from home due to the pandemic was equal to 36.6%. That represented a turning point in the way to conceive working activities. Indeed, people learned from this experience that a different way to organize private and work life was possible, and they started to wonder about the benefits connected to the possibility of adopting homework as a regular practice, even after the pandemic [4]. Already in June 2020, results of surveys conducted by Deloitte on 10,000 employees across seven European countries reported that a large number of workers (34% of the interviewees) expressed a desire for increased flexibility and autonomy in determining when and how they carry out their work after the end of the emergency [5]. Moreover, according to a Eurofound analysis conducted during February and March 2021 in the EU 27 [3], 30.6% of the interviewees stated that, if they had the choice, they would have liked to work from home several times a week. A study by the Pew Research Center about the perspective of homeworking in America after the pandemic, published in February 2022 [6], stated that employed adults who declared that the responsibilities of their job could be performed at home and who worked from home all/most of the time in the period they were interviewed were 71% in October 2020 and 59% in January 2022.

Considering that residential buildings are specifically designed for housing needs, they could be not proper to host comfortable workstations provided with all comforts, i.e., designed according to ergonomics and environmental control principles—thermohygrometric comfort, air quality, proper soundproofing—among which lighting quality plays surely a crucial role. Light is essential to see and to work, but it affects people's well-being in multiple ways, influencing physical and mental processes, including mood, cognition, regulation of the circadian system, alertness, as well as cognitive performance and productivity [7–9]. For these reasons, it is necessary not only to correctly design electric light but especially to guarantee a proper amount of daylight in the home workstation. Actually, often inside private houses, a space specifically dedicated to work activities, i.e., a space where to have calmness to concentrate, equipped with a personal computer and internet connection and a dedicated desk and a comfortable chair is not present, so workstations are arranged in spaces originally designed for other purposes (bedrooms, dining rooms, kitchens) [10–13]. For this reason, it could be difficult to adapt lighting to the new needs, and home-workers could experience discomfort conditions.

With the spread of the homeworking phenomenon, the study of lighting conditions and especially of daylighting in home workstations became an urgent need, and researchers started investigating this topic to identify which problems people must face to arrange a home workstation. That was considered essential in the perspective of giving guidelines, spreading good practices, and providing the employees with all the resources to guarantee a safe and comfortable working time [14]. Especially considering daylight provision, this analysis is not an easy task due both to the natural differences in climatic conditions over the world and to the variety of residential buildings' architectural configurations, in turn depending on the regional building culture.

To describe this variety of conditions, research based on surveys can be useful. For example, Amorim et al. [15] investigated homeworkers' perception of the luminous environment in Brazil and Colombia, trying to underline the regional differences. As regards daylight, they found that it was more appreciated than electric light and that interviewees leaving between the latitudes of 20° S and 34° S expressed lower satisfaction with the visual environment. Another interesting study is that by Aslanoğlu et al. [16], who spread online a questionnaire in July–August 2020 covering the U.K., Poland, Sweden, and Turkey, in which they requested information regarding lighting conditions, both natural and electric. They underline the different habits of daylight control in different regions. For example, they observed that the most predominant type of shading system varied on the location (blinds in the case of Turkey, interior curtains in the U.K., Poland, and Sweden). Bellia et al. [13] launched an online questionnaire aimed at students and homeworkers who were compelled to stay at home due to the COVID-19 pandemic about daylight and electric light characteristics in home workspaces. As regards daylight, they found that there was no predominant window exposure, even considering different room types and that the window size was very different case by case. Moreover, it was found that, although daylight amount was generally considered sufficient, sometimes people complained about its insufficient provision due to the obstructing presence of protruding balconies and neighboring buildings.

Based on these considerations, it would be interesting to understand how the daylight conditions can vary in home workstations, according to some of the listed parameters, for example, the windowed area or the placement of the building in the urban context and its orientation, to infer useful information about residential buildings design considering the new arising urgent needs.

In this perspective, apart from surveys, another useful tool to investigate daylight provision in houses is undoubtedly the "Climate-based Daylight Modelling" (CBDM). CBDM allows us to easily analyze daylight amounts inside buildings, considering both the weather characteristics specific to each country and the different building configurations [9]. Moreover, in recent years, researchers have proposed different parameters allowing us to evaluate both the overall daylight amount, considering the implications on energy issues, and non-visual effects due to daylight exposure [17–19].

As for energy savings, one of the most common concepts is Daylight Autonomy (DA) [9]. It can be expressed as "the fraction of the occupied time when an illuminance threshold is reached by daylight alone", regarding the influence on circadian rhythm regulation, a recent concept known as Circadian Stimulus Autonomy (CSA) has been proposed. It can be described as "the percentage of time during which a specific threshold of Circadian Stimulus (CS) is met solely by daylight [20] during the morning". In turn, the CS represents the percentage of nocturnal melatonin suppression [21] resulting from a standardized one-hour light exposure. Thus, the calculation of CSA is grounded in the concept of DA, defining the illuminance threshold through the spectral power distribution (SPD) of the received light. To ensure effective circadian entrainment, it is recommended to maintain a Circadian Stimulus (CS) value of 0.4 or higher during the early morning hours [22]. For this reason, the CSA can be calculated considering the daylight illuminance values corresponding to a CS equal to 0.4 according to the specific SPD at the eye and occupancy hours from 8:00 to 9:00 a.m.

1.2. Objectives of the Study

The objective of this study is to assess, based on lighting and health parameters, the appropriate window design for standard living rooms in residential buildings, as nowadays, these spaces are often used for mixed purposes such as teleworking or studying. This work assesses the impact of climatic conditions, using the example of three representative European cities—London, Milan, and Seville—as well as the orientation and presence of remote obstructions, such as other surrounding buildings. The quantification of the impact of window size on visual comfort and energy consumption in electric lighting, as well as in human well-being, is carried out using the dynamic lighting metrics DA and CSA.

The methodology used includes the definition of the study model, the choice of locations and orientations, the selection and validation of the calculation tool, and the selection of metrics for analysis.

2. Method

The initial step of the methodology involves the creation of a virtual model of a standard bedroom or living room of a dwelling, which has a single window, considering that this space can also serve as a home office for remote work. This study also considers the possibility of transforming the bedroom into a dedicated teleworking space, thereby losing its function as a resting area. The simulations were performed by placing the model in three different cities—London, Milano, and Seville—covering a wide range of weather conditions and latitudes, spanning from 37° to 50°. This analysis contributes to understanding the influence of sky luminance and latitude. As a result, the findings from Milano and Seville may be applied to other regions with a Mediterranean climate, while the conclusions drawn from the city of London can be applied to other regions of Septentrional Europe.

In addition, calculations have been carried out taking into account the window facing both South and North. This approach was taken to account for a broad range of European latitudes and sky types. Finally, the effect of a remote obstruction is studied as a variable. This obstruction is arranged in a manner that decreases the visible sky fraction from the window to four levels: 30°, 45°, 60°, and 90°.

The adequate visual comfort and energy savings in electric lighting attributed to daylight are determined through the analysis of results provided by the dynamic metrics, using a calculation engine that has been previously tested under real conditions in one of the locations under study. Once the tool has been validated, DA is employed to measure the fraction of occupied time when electric lighting remains turned off. Moreover, the CSA is used to evaluate the effect of daylight exposure on circadian rhythm regulations.

As previously mentioned in the introduction, the evolution of biological markers induced by daylighting is analyzed by quantifying melatonin suppression, which is achieved through the parameter known as CS. Thus, by considering an illuminance value and a resulting spectrum perceived by the observer's eyes, the CSA has been assessed.

2.1. Definition of the Model

The virtual space used in this study is based on a standard bedroom measuring 3.0 m in height, 3.0 m in width, and 6.0 m in depth. This room can also serve as a home office for remote work. The room has a single window, with a visible transmittance of 0.74 and measuring 1.2 m in height, which is located in the center of one of its short sides. Figure 1 shows the reflectance values of the room surfaces. These dimensions, approximately 18 m^2, are typical for a standard bedroom or small living room equipped with a wardrobe and an office desk. The reflectance values follow the recommendations of EN 12464-1 for office workspaces, with ceiling reflectance values ranging from 0.7–0.9, wall reflectance values from 0.5–0.8, and floor reflectance values from 0.2–0.4.

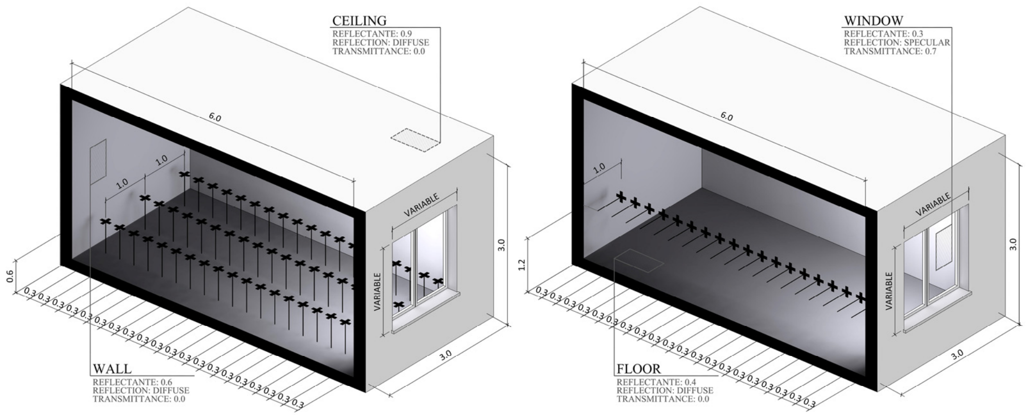

Figure 1. Room model dimensions and Location of Calculation Points for Energy Efficiency Calculations (**left**) and for circadian stimuli trials (**right**).

For the DA calculations, three longitudinal arrays of points were used, with horizontal illuminance values calculated at intervals of 0.3 m at 0.8 m above the floor, as shown in Figure 1. The first one is positioned along the central axis of the model (center), and the second and third ones are located 0.5 m from the longer walls. For CSA, as shown in Figure 1, a line of vertical illuminance points was used, located at 0.5 m from the lateral wall, considering a distance between the studied points of 0.3 m and a height above the floor of 1.2 m. These points faced the rear wall, simulating the view of an occupant from his seat with the desk facing one of the side walls.

The spectral reflectance of the inner surfaces within a room is crucial in determining the resulting spectral irradiance perceived by the observer's eye. Consequently, it is instrumental in evaluating the CS. This is particularly important when the occupant is working facing a wall. Figure 2 represents the spectral reflectance of each of the inner surfaces of the model, which affects the resultant spectrum perceived by the eye's observer. Assuming an average observer position, the field of view is occupied by the wall surface by 40%. The ceiling and floor each occupy 10% of the field of view, while the window and desk each also occupy 20% of the view [23].

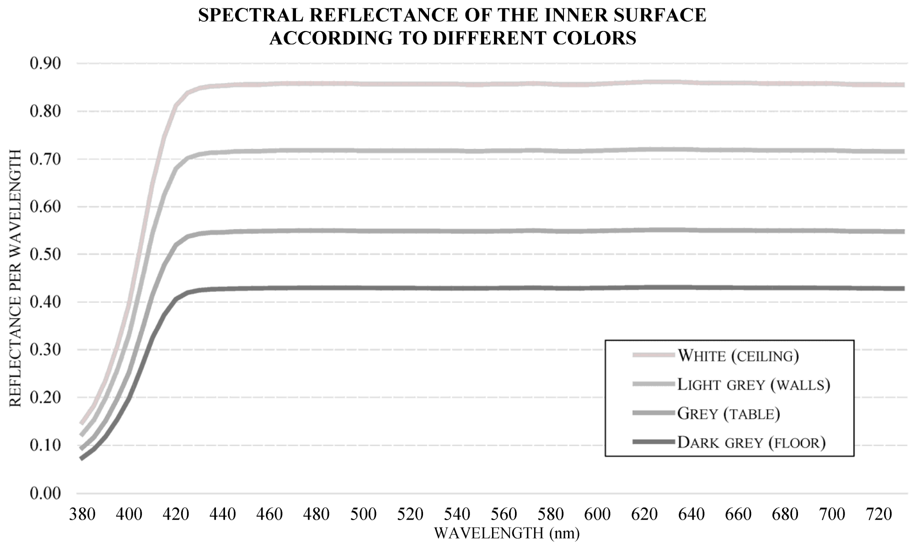

Figure 2. Values of the spectral reflectance of each inner surface of the model.

2.2. Remote Obstructions

As multi-family homes are typically situated in established urban areas, they often face remote obstructions, such as adjacent buildings, which can limit the view of the sky. To evaluate the impact of these obstructions on natural light accessibility, a vertical plane is proposed to be positioned in a way that reduces the visible sky component from the window to four levels: 30°, 45°, 60°, and 90°, as it can be seen in Figure 3. This vertical plane has a reflectance of 0.60, thus representing the façade of a multi-family building with windows and different shades of carpentry and walls.

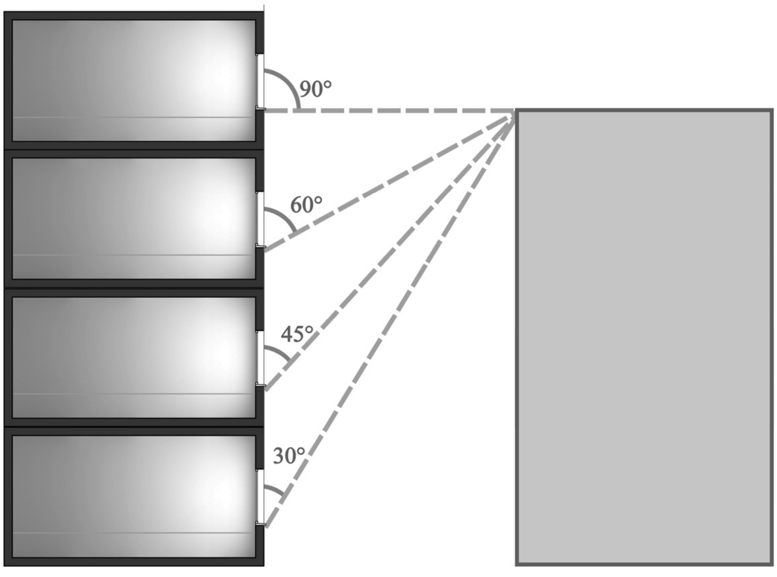

Figure 3. Visible sky fraction angles from the window of the room under study due to remote obstructions.

2.3. Location of the Room and Orientation of the Window Opening

To ascertain, by means of dynamic metrics (DA and CSA), both the appropriate dimensions for the window of the teleworking room and the impact of remote obstructions, the studied room model was simulated in three European cities, as can be seen in Table 1. It was performed to encompass a sufficient range of climate conditions. Weather data were collected from the EnergyPlus reference [24].

Table 1. Geographical conditions of the cities studied.

City	Code	Latitude	Longitude	Time Zone	Percentage of Hours With		
					Direct Sun	Clear Skies	Overcast Skies
London	LON	51°30′ N	−0°7′ O	GMT +0	72%	25%	36%
Milano	MIL	45°28′	9°11′ E	GMT +1	75%	20%	29%
Seville	SEV	37°22′ N	−5°58′ O	GMT +1	81%	31%	32%

The model was oriented in both the North and South directions to assess the analyzed dynamic metrics. The benefits of window facing, in terms of visual comfort and circadian entrainment, vary depending on both the room's orientation and its occupancy pattern. As the room is typically occupied for the majority of the day, spanning from morning to evening—as it serves as a teleworking area—the selection of both North and South orientations permitted the acquisition of DA values, representing the minimum and maximum achievable—the best and worst-case scenarios in terms of energy savings and visual comfort—and CSA values that can be regarded as the average [23,25].

To evaluate the CSA, it is necessary to consider the daylight SPD. Therefore, an average value of SPD for the sky was created according to the climatic conditions and latitudes of the three locations. The average SPD of the sky for three different latitude regions, namely southern, middle, and northern Europe, is shown in Figure 4. This data was generated using statistical information on the frequency of overcast skies [24] and the climatic characteristics of each location. In addition, the typical SPD for northern Europe—known as CIE D65—is presented. As shown in Figure 4, the SPD for northern locations is similar to a CIE D50 sky type—a typical overcast sky. Meanwhile, the SPD curve for middle locations bears a resemblance to the CIE D65 distribution. Moreover, southern European locations, where clear skies are common, show a slightly higher SPD value in the short wavelength range when compared to the CIE D65 distribution.

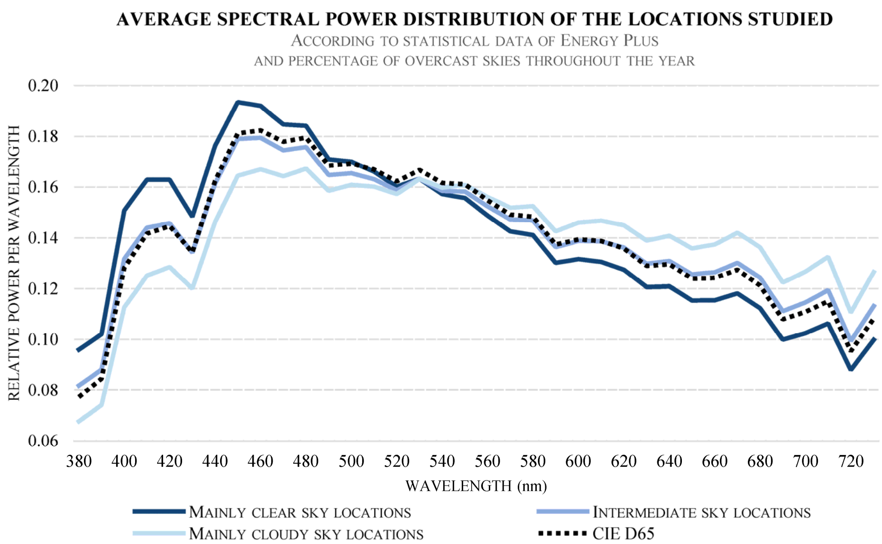

Figure 4. Average spectral reflectance values of the inner surfaces of the room.

2.4. Parameters of the Simulation Tool

The lighting simulation carried out in this study and contrasted with the monitoring of an existing test cell were conducted using the DaySim 3.1, a simulation tool equipped with the Radiance engine, which includes the dynamic metrics for the current sky conception [26]. Prior research [27–31] has validated this engine by comparing it with real scenarios and the CIE test cases [30].

2.5. Calculation Metrics

The analysis of the influence of window size and remote obstructions of the room-workspace hybrid's energy savings and circadian entrainment required two distinct dynamic daylighting metrics: DA and CSA. DA (daylight autonomy) can be expressed as "the percentage of the year when a minimum illuminance threshold is achieved solely by daylight". Thus, a higher DA value signifies reduced consumption of electric lighting, as expressed in Equation (1) [9]:

$$DA = \frac{\sum_i wf_i \cdot t_i}{\sum_i t_i} \in [0,1] \quad wf_i = \begin{cases} 1 \; if \; E_D \geq E_L \\ 0 \; if \; E_D < E_L \end{cases} \tag{1}$$

where t_i defines the "occupied time of the studied room, represented as a time interval per day", w_{fi} is the "weighting factor which depends on the illuminance threshold", E_D is the "daylight illuminance defined at a given point", and E_L is the "illuminance threshold defined by lighting requirements".

DA provides a means to quantify the energy usage produced by electric lighting by determining the duration over the course of the year during which the luminaires should remain switched on to maintain the specified illuminance threshold [31]. The establishment of illuminance thresholds is closely connected to the minimum daylight illuminance value necessary on the work plane in the bedroom to facilitate efficient office task performance.

For energy consumption and visual comfort analysis, occupancy hours were considered only on weekdays, aligning with a full working day comprising two shifts, spanning from 8:00 a.m. to 5:00 p.m. [31]. The standard implementation of Daylight Saving Time (DST) was also taken into account. Moreover, the assessment of the energy consumption due to electric lighting was performed using an assumed energy efficiency rate of 2.00 W/m^2·100 lx, along with a switching system that independently controls the lines of luminaires.

Another metric of this study is CSA (circadian stimulus autonomy), which is focused on evaluating the proper circadian entrainment. As seen in the background, CSA is defined as "the percentage of days when a threshold for adequate melatonin suppression is met solely by daylight during a specific time of the day, typically in the morning" [17,20,23]. CSA is primarily influenced by the SPD and the illuminance perceived in terms of circadian light (CL_A). The calculation of CS is based on the phototransduction model established by Rea et al. [21], according to Equation (2) [20]:

$$CS = 0.7 \cdot \left(1 - \frac{1}{1 + \left(\frac{CL_A}{355.7} \right)^{1.1026}} \right) \tag{2}$$

The CS value is directly related to the predicted degree of light-induced melatonin suppression, varying from the full suppression (0.0) to the saturation threshold (0.7). This determination is based on an hour-long exposure period and considers an eye with a pupil size of 2.3 mm. According to previous research [22], a CS value of 0.4 is considered suitable for achieving appropriate circadian entrainment.

CSA calculations are associated with the minimum light exposure required by the human eye to achieve the appropriate circadian stimulus—equivalent to a CS value of

0.4 [22]. This CS value is determined by the combined SPD of the light—the natural light SPD adjusted by the reflections on the inner surfaces of the room—as well as the light flux received. Hence, CSA calculations must have established an illuminance threshold that ensures the attainment of a minimum CS value of 0.4, taking into account the resulting SPD of the studied cities.

For the assessment of adequate circadian entrainment in the bedroom model used for teleworking, the evaluation period is during weekdays, from 9:00 a.m. to 10:00 a.m., which typically corresponds to the start of a regular workday [31,32].

Figure 5 illustrates the average spectral irradiance distribution from the SPD of each type of sky, taking into account the indoor reflections for the three location groups (southern Europe, Central Europe, and Septentrional Europe) presented in Figure 4. This distribution was used to calculate the CSA. It is important to note that all the SPDs analyzed exhibited a significant reduction in the short wavelength fraction, as the spectral reflectance values of the inner surfaces of the room are diminished for these wavelengths.

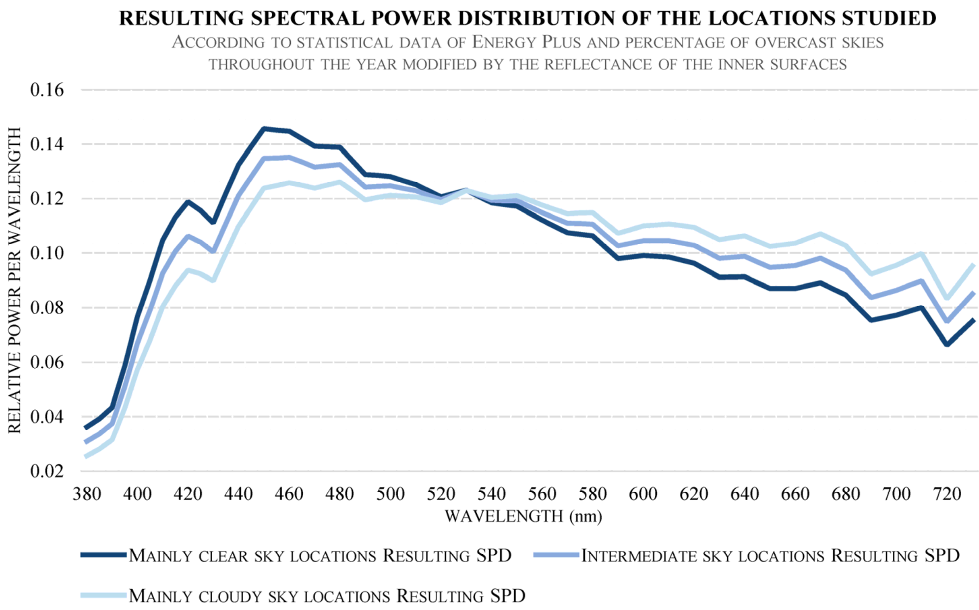

Figure 5. Resulting spectral irradiances of daylight for the cities under study, determined from statistical data and modified by the inner reflections in the model [23].

Based on both the resulting SPDs depicted in Figure 5 and the minimum CS value of 0.4, the minimum illuminance thresholds were determined using Equation (2), as shown in Figure 6. As indicated by Figure 6, locations in the South with clearer skies require a lower illuminance compared to cities situated at higher latitudes with worse weather conditions to achieve the same CS value. Nevertheless, it is also worth noting that an illuminance value of 300 lx yields a CS value within the range of 38% to 41%, depending on the climate conditions. Consequently, this study can establish the illuminance threshold for CSA as 300 lx for the cases under examination.

In summary, it can be deduced that the SPD of the sky has a limited influence on the resulting CS, except in extreme situations, such as during dawn or dusk. Moreover, the fluctuation in the CS obtained is noteworthy, primarily within the illuminance range of 300 to 2000 lux. Below 300 lx, it is insufficient to facilitate proper circadian entrainment—with a CS value below 0.4. Conversely, beyond 2000 lx, the CS value tends to stabilize at approximately 0.7.

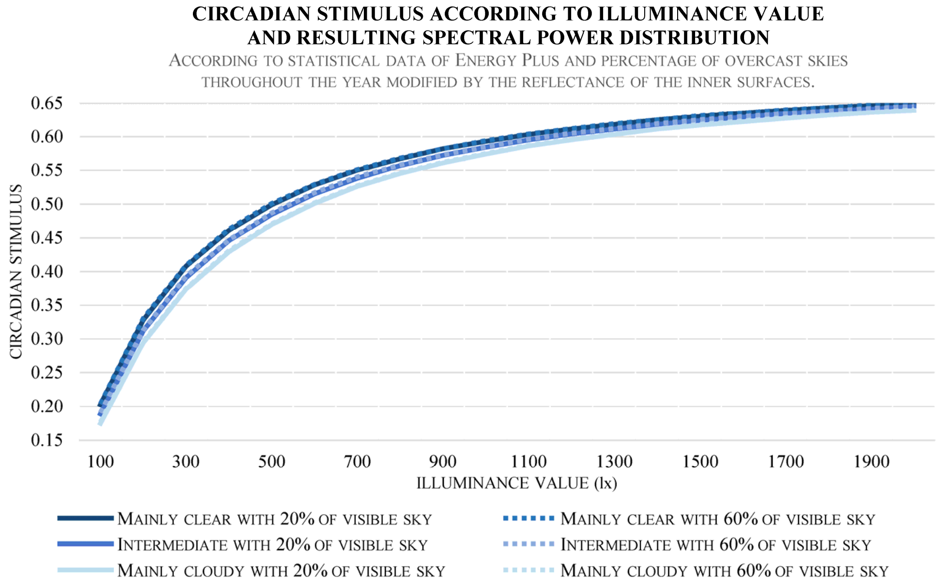

Figure 6. CS obtained per each illuminance value obtained, based on the spectral irradiances shown in Figure 5.

2.6. Validation of the Calculating Tool

A DA comparison test was carried out using the illuminance measurements from a test room [23,32]—located in the city of Seville, Spain—as a contrast, as shown in Figure 7A. The proportions, window location, and reflectance values of this test cell are similar to those described in the room-workspace hybrid model. Since the room was originally designed to emulate a bedroom in a dwelling, it has dimensions of 3.2 m in depth and 2.4 m in width, with a free height of 2.7 m, as illustrated in Figure 7A. It features a south-facing double-glazing window that measures 116 cm in width and 108 cm in height. Both walls and ceiling have an internal reflectance of 0.72, while the floor has a reflectance value of 0.22 [23,31,32].

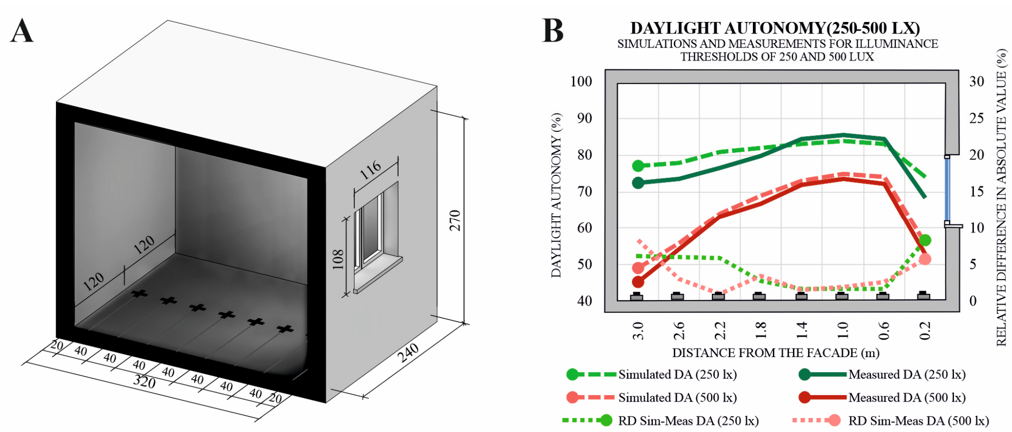

Figure 7. (**A**) Size of the test cell with the distribution of the illuminance meters; (**B**) DA values from illuminance measurements and simulation, where RD is the Relative Difference in absolute value (%).

The eight illuminance meters were positioned along a central line with a spacing of 40 cm, as illustrated in Figure 7A. The experiment was carried out over the course of the entire year 2017 [32]. The simulation tool replicated the location of these sensors with its calculation grid, as depicted in Figure 7B.

The occupancy schedule was configured to mimic typical office working hours, running from 8:00 a.m. to 5:00 p.m., with illuminance thresholds set at 250 and 500 lux.

DA values for both illuminance thresholds are shown in Figure 7B, obtained both from simulation and measurements. The DA comparison process showed that the highest maximum deviation between them was 8.4%—for the 500 lx threshold—with 1.9% bias error and 6.6% standard deviation (95% reliability). All the indicators were below the 10% deviation threshold.

These findings serve to establish the proficiency of DaySim 3.1 in accurately computing the dynamic metric DA—and, consequently, for CSA—for spaces that share similar dimensions and boundary conditions.

3. Results

3.1. DA and CSA Based on the Window Size

Once this simulation software has been validated with an existing test room in one of the studied locations, the simulation results are provided, described in a set of room sections—which represent the typical environment for a teleworker—where the analyzed dynamic metrics are shown. Figure 8 represents the room sections for the location with mainly clear skies—Seville—both for South and North orientations, without external obstructions, according to a variable window size—from 10 to 40% of the window façade ratio. As seen in Figure 8, the blue solid line represents DA in the central axis for a threshold of 300 lx, and the dashed blue line shows these results for the side axis, as previously described in Figure 1. The amber solid area describes the energy consumption linked to DA values, considering that the energy efficiency of the luminaires is 2.0 $W/m^2 \cdot 100$ lx. Finally, the red dashed line describes the values of CSA obtained in the vertical section, as also described in Figure 1.

3.2. DA and CSA According to External Obstructions

The second representative set of room sections corresponds to Figure 9, where the external obstructions are considered as the variable parameter. The section views are located in Seville with a medium-sized opening—window to façade ratio (WtF) of 30%—while the visible sky fraction varies from 30 to 90°, as outlined in the methodology.

3.3. DA and CSA According to Climate Conditions

One of the main parameters for evaluating the accessibility of natural lighting in the studied rooms is the climate conditions. Figure 10 represents the room sections for the location with mainly overcast skies—London—intermediate skies—Milano, and predominantly clear skies—Seville—considering a fully visible sky from the window.

Finally, Figure 11 represents the same room sections described above in Figure 10, although considering an external obstruction that provides a visible sky fraction of 45°. This analysis is decisive since the higher the external obstruction, the lower the influence of climate conditions, which also depends on the window orientation.

For the sake of brevity, not all calculation models have been represented in Figures 8–10, despite the fact that the discussion section addresses all results obtained, including those not described in the previous figures.

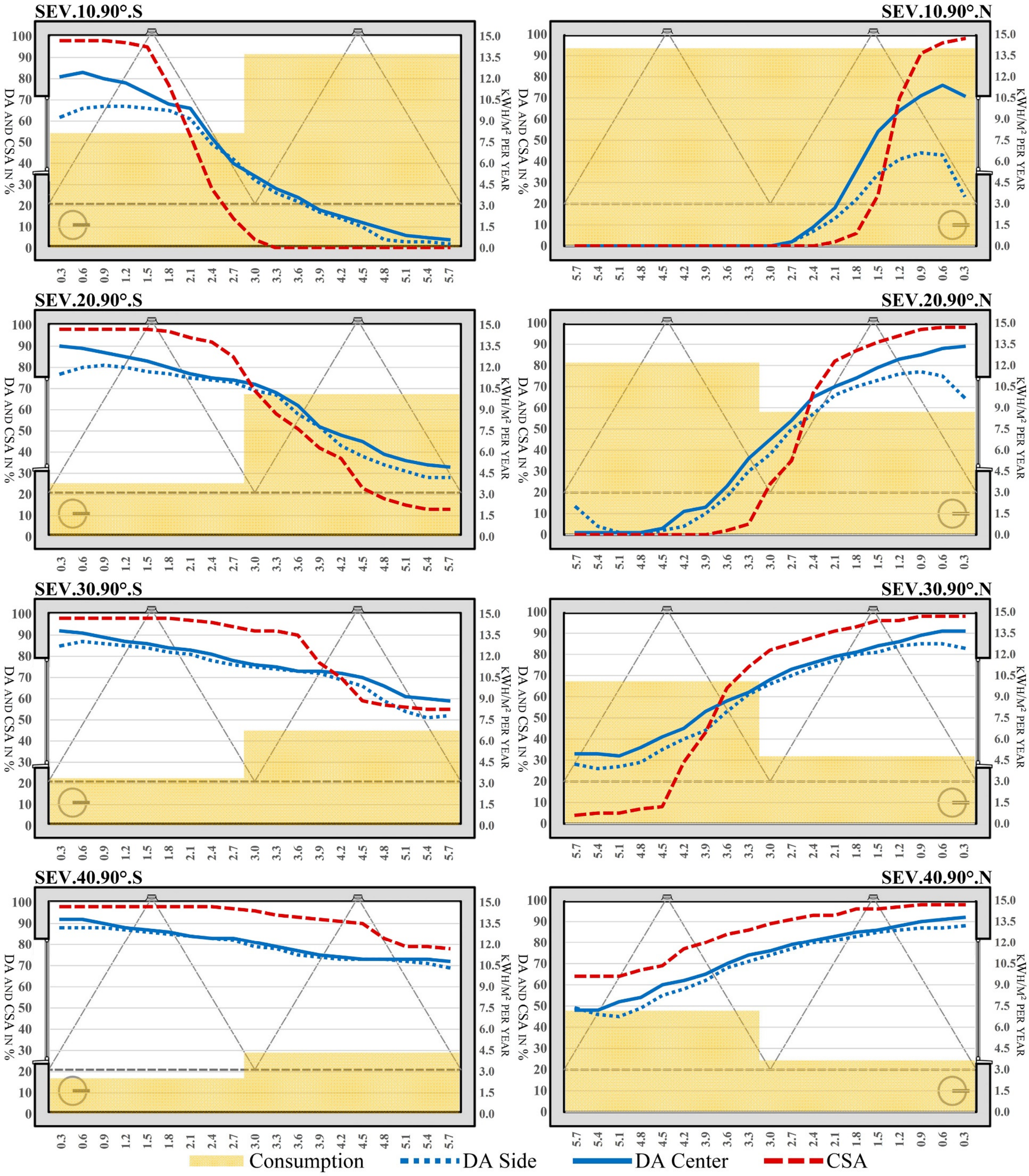

Figure 8. Vertical sections of the models for the location with mainly clear skies (Seville) without external obstructions, considering a variable window size (from 10 to 40% of window to façade ratio) for South and North orientations, showing the evolution of DA (300 lx) in the horizontal plane with its equivalent energy consumption and the values of CSA (300 lx) in the vertical plane.

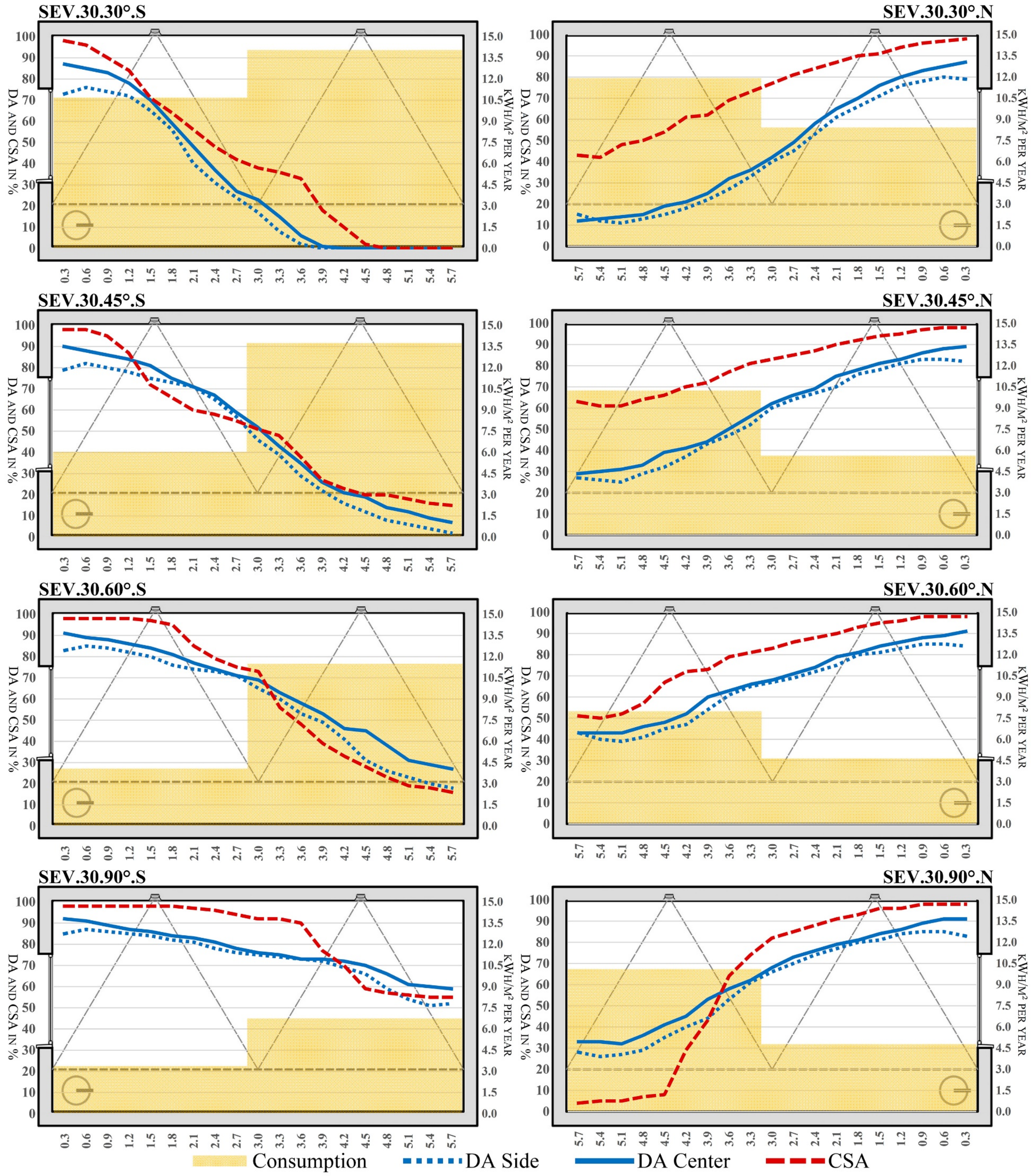

Figure 9. Section views of the calculation models for the location with mainly clear skies (Seville) with a WtF ratio of 30% for South and North orientations, considering a variable visible sky fraction (from 30° to 90°), showing the evolution of DA (300 lx) in the horizontal plane with its equivalent energy consumption and the values of CSA (300 lx) in the vertical plane.

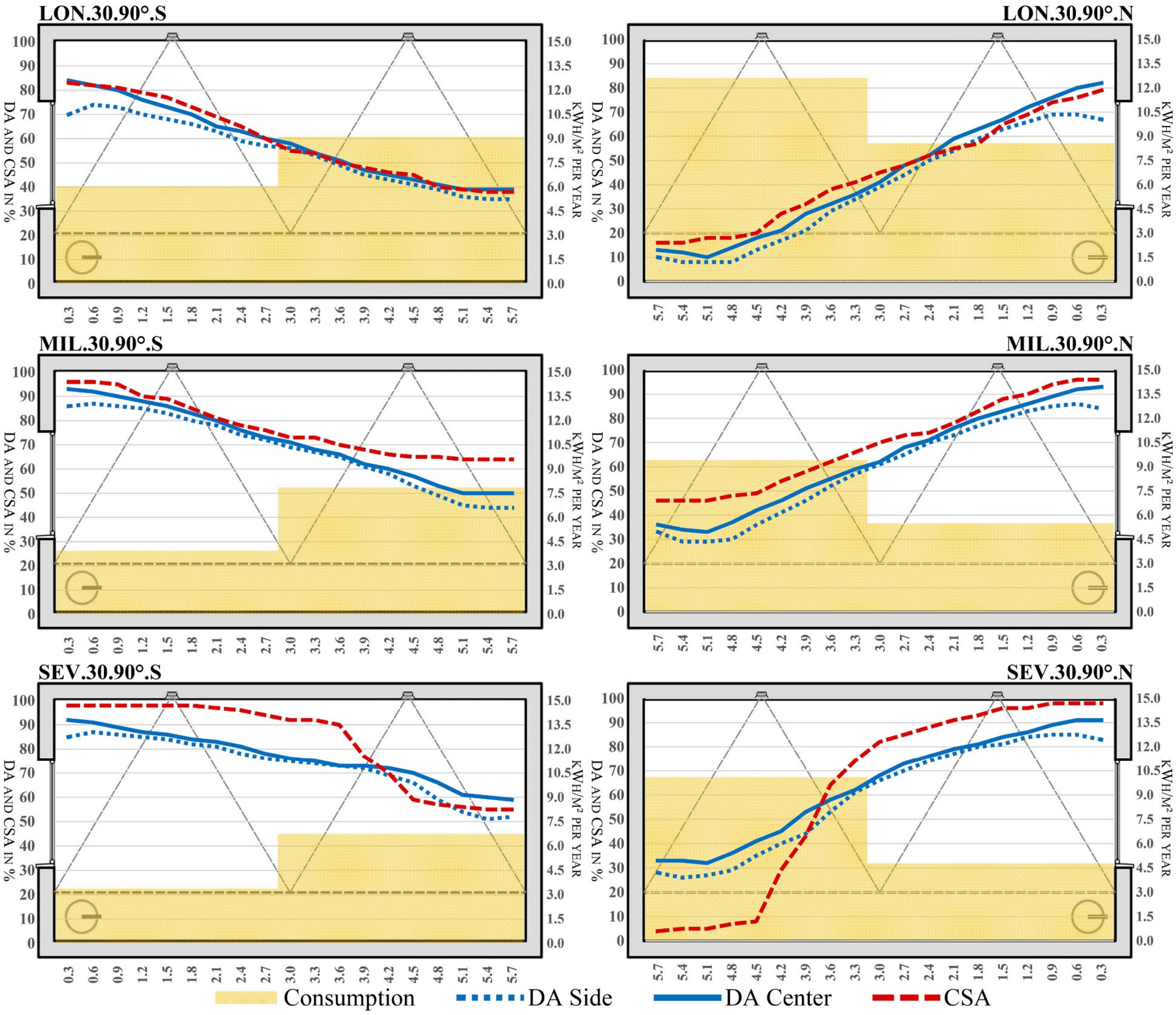

Figure 10. Vertical sections of the models for locations with mainly overcast skies (London), intermediate skies (Milano), and predominantly clear skies (Seville) with a WtF ratio of 30% for South and North orientations without external obstructions, showing the evolution of DA (300 lx) in the horizontal plane with its equivalent energy consumption and the values of CSA (300 lx) in the vertical plane.

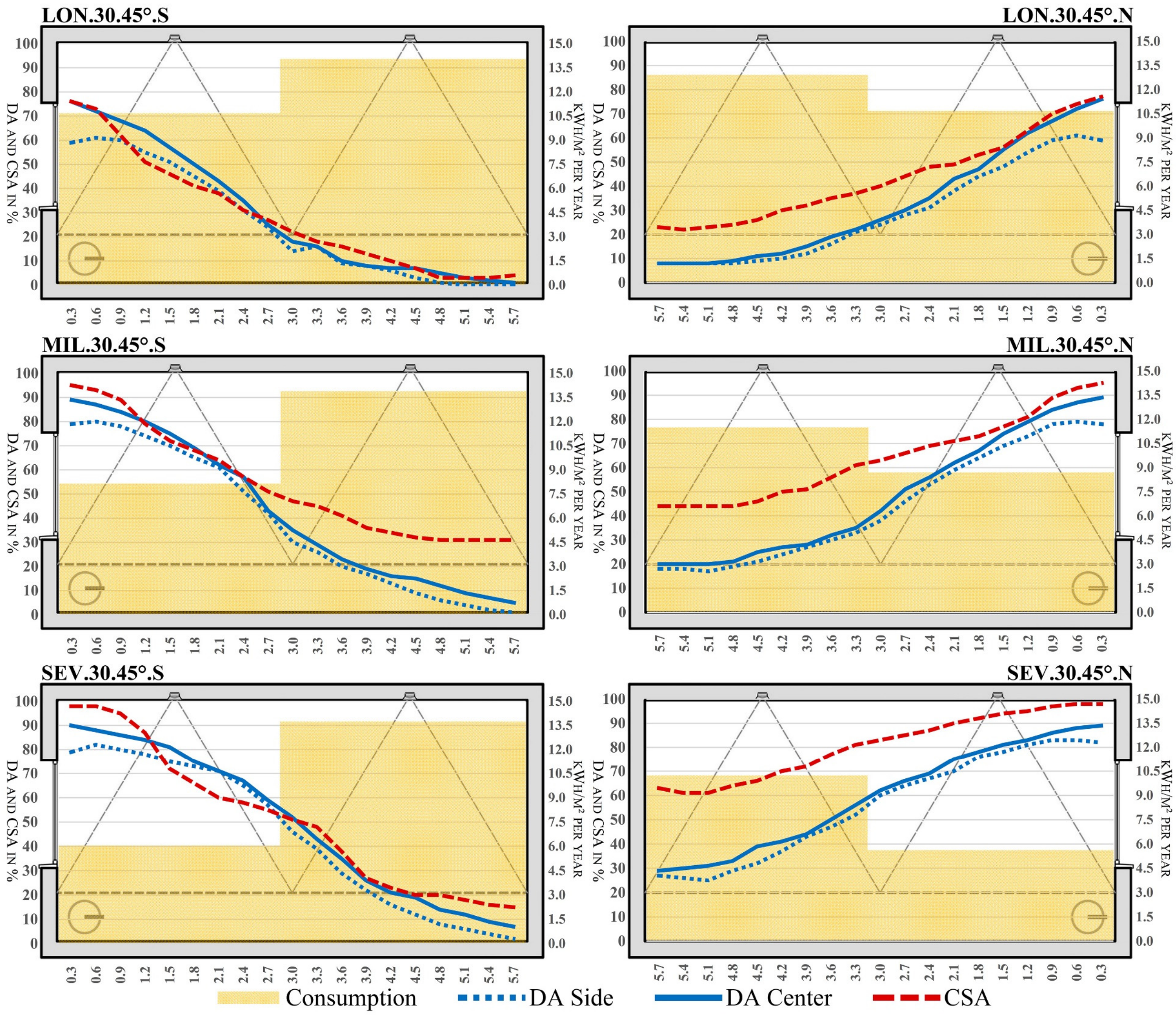

Figure 11. Vertical sections of the models for locations with mainly overcast skies (London), intermediate skies (Milano), and predominantly clear skies (Seville) with a window façade ratio of 30% for South and North orientations, with a visible sky fraction of 45°, showing the evolution of DA (300 lx) in the horizontal plane with its equivalent energy consumption and the values of CSA (300 lx) in the vertical plane.

3.4. Analysis of Results

As deduced from Figure 8, a window taçade ratio (WtF) of 10% cannot provide minimum circadian entrainment, irrespective of the external obstructions and the climate conditions. A sufficient visual comfort—which can be assumed when the DA value is equal to or higher than 50%—only occurs in the area close to the façade—up to 1.2 or 1.8 m from the façade for North orientation and up to 2.1 or 2.4 m from the window for South orientation, depending on the climate conditions.

Moreover, a medium-sized window without external obstructions—opening to façade ratio of 30%—allows sufficient circadian entrainment—assumed as when the CSA value is equal to or higher than 50%—up to the middle of the space for North orientation—2.7 or 3.6 m from the façade depending on the climate conditions. Analyzing the scenario with a window facing South, a CSA value equal to or higher than 50% is achieved across the entire surface of the model, except in those cases with mainly cloudy skies—particularly the London location.

Following the analysis of the impact of the external obstructions and as partially described in Figure 9, the studied dynamic metrics for a room model with a window facing North tend to reach higher values toward the rear of the model when there is an external obstruction with a visible sky fraction of 45°, that is to say, the externally reflected component balances the illuminance between the front and the back of the room, providing better results than a window without obstructions. Of course, this assertion depends on a minimum visible sky fraction—lower than 45° is insufficient—and a minimum reflectance of the exterior obstruction. The opposite occurs for windows facing South; the external obstructions reduce the daylight illuminance inside the room and, therefore, the benefits of visual comfort and circadian entrainment.

Finally, as deduced from Figures 10 and 11, the climate conditions notably affect the visual comfort and the circadian response of teleworkers. Considering a scenario without remote obstructions, a room located in London—with a predominance of overcast skies—requires a large opening—a WtF ratio of 40%—to meet similar results to those of a model with a medium-size window—WtF ratio of 20%—with mainly intermediate or clear skies. According to a scenario with remote obstructions and a window facing South, the impact of the climate conditions is reduced by the daylight blocking of the outdoor obstacle, although this convergence is not observed for North orientation, where the externally reflected component gives relevance to the luminance of the sky vault.

4. Discussion

The results shown above are analyzed by comparing different parameters of the studied model, which are decisive in the indoor daylight levels, with the aim to promote an appropriate circadian stimulus and adequate visual comfort, determining the relationship between CSA and DA values according to different scenarios.

4.1. DA and CSA According to Window Size

The initial trial compares the differences of the analyzed dynamic metrics in accordance with the dimensions of the window. Figure 12A represents the relative difference of DA of three windows sizes—WtF ratio of 10, 20, and 30%—in comparison with a large opening—WtF ratio of 40%—both for North and South orientations, taking into account that the studied location is Seville—with predominantly clear skies—and considering that there are no external obstructions in this analysis. Figure 12B represents the same study focused on the CSA results.

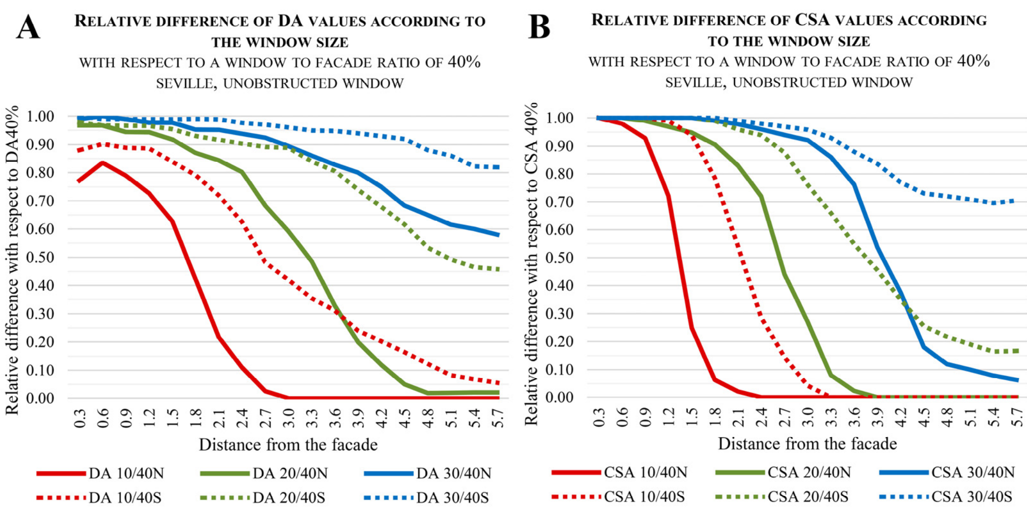

Figure 12. The relative difference of the studied metrics as a function of the dimensions of the window, with respect to a WtF ratio of 40%, considering a location with mainly clear skies (Seville) and without external obstructions. (**A**) DA values. (**B**) CSA values.

As deduced from Figure 12, there is not a noticeable divergence of DA and CSA in the surface near the window—from 0.0 to 1.5 m—irrespective of the window size, except in those cases with small openings—SEV.10.90° S and SEV.10.90° N. Therefore, the surface near the window is used to provide suitable visual comfort and a good circadian entrainment, independently of other architectural parameters.

Analyzing the work plane in proximity to the rear of the room, the relative difference of DA values, according to the window size, corresponds approximately to 40% compared to similar openings—SEV.40.90° S versus SEV.30.90° S or SEV.30.90° S versus SEV.20.90° S, as seen in Figure 12A. Focusing on the case of CSA, observed in Figure 12B, this divergence rises up to 55%, so the window size is decisive in the utilization of daylight in the vertical plane. It must be noted that the illuminance distribution in the vertical plane may change according to the external obstructions, addressed in a subsequent analysis.

Finally, the difference between DA and CSA values is provided by smaller openings—SEV.10.90° S and SEV.10.90° N—tend to be lower in the case of South orientation with respect to North orientation, as deduced from Figure 12A,B. Therefore, the influence of the window size on the indoor daylight levels—both in the horizontal and vertical planes—used to be higher for windows facing South, considering an unobstructed opening.

4.2. DA and CSA According to External Obstructions

The second trial addresses the impact of the external obstructions. Figure 13A shows the relative difference of DA of three visible sky fractions from the window—30, 45, and 60°—with respect to an unobstructed opening, as in the previous case, both for North and South orientations. Unlike the previous trial, the selected location is Milano, and the window size for all scenarios corresponds to 30% of the façade surface—a medium-large window. As in the previous trial, Figure 13B represents the same analysis for CSA values.

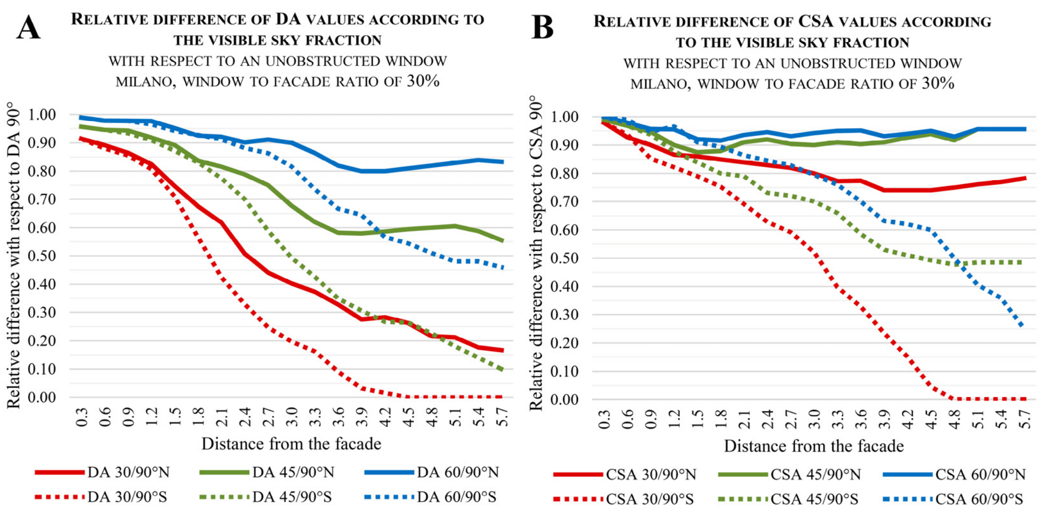

Figure 13. The relative difference of the studied metrics as a function of the visible sky fraction, with respect to an unobstructed window, considering a location with mainly intermediate skies (Milano) and a window façade ratio of 40%. (**A**) DA values. (**B**) CSA values.

Studying the impact of the external obstructions, it can be deduced from Figure 13A,B that a visible sky fraction of 60° for a window facing North allows similar values of DA and CSA than an unobstructed opening—MIL.30.60° N compared with MIL.30.90° N. In the case of South orientation, the analyzed dynamic metrics decrease up to 45% for the same scenario in the surface of the back of the room—MIL.30.60° S compared with MIL.30.90° S—keeping a similar value in the zone close to the window—from 0.0 to 3.0 m. Accordingly, the external obstructions can benefit those windows that avoid the solar path, as in the case of North orientation, unlike the case of openings with South orientation.

As deduced from Figure 13A, an external obstruction of 45° reduces DA values toward the rear of the model up to 55%, in comparison with an unobstructed opening—MIL.30.45° N compared with MIL.30.90° N. On the other side, the reduction of CSA in the same scenario is almost negligible. Therefore, it can be deduced that daylight-linked controls (DLCs) can still be useful in scenarios with a visible sky fraction of 45°.

Finally, as deduced from Figure 13A,B, an external obstruction of 60°—that is to say, a visible sky fraction of only 30°—notably reduces the studied dynamic metrics, except in those cases where CSA is analyzed, and the window is facing North—MIL.30.30° N compared with MIL.30.90° N—where the reduction of this metric is lower than 20%. Accordingly, rooms with high external obstructions and North orientation could count on DLCs when the promotion of circadian stimulus is needed and the externally reflected component is noticeable.

4.3. DA and CSA According to Climate Conditions

The final trial corresponds to the examination of the influence of the climate conditions on the studied dynamic metrics and, therefore, on the visual comfort and the circadian entrainment of the workers in the defined environments. Figure 14A describes the relative difference of DA of locations with mainly overcast and intermediate skies—London and Milano, respectively—with respect to the studied location with mainly clear skies—Seville, considering North and South orientations, a WtF ratio of 30% and a visible sky fraction of 60°. As in the previous figures, Figure 14B shows a similar analysis conducted for CSA values.

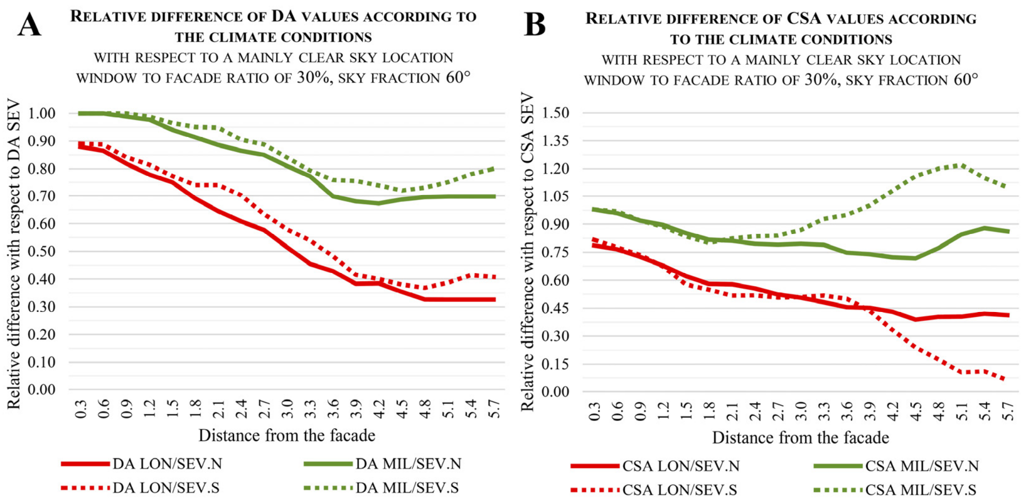

Figure 14. The relative difference of the studied metrics as a function of the climate conditions, with respect to a mainly clear sky location (Seville), considering a WtF ratio of 30% and a visible sky fraction of 60°. (**A**) DA values. (**B**) CSA values.

Analyzing the impact of the climate conditions on DA values, it can be concluded that there is not a significant divergence in the work plane near the window—from 0.0 to 1.5 m—irrespective of the climate conditions. Therefore, this area close to the opening is suitable for promoting good circadian entrainment and sufficient visual comfort, irrespective of the window size—as deduced before—and the climate conditions, taking into account a minimum visible sky fraction of 60°.

As observed in Figure 14A, a location with mainly clear skies—SEV.30.60° S and SEV.30.60° N—provide an increase of DA up to 30% in the work plane at the back of the room with respect to locations with predominantly intermediate skies—MIL.30.60° S and MIL.30.60° N—which in turn offer an increase of around 35% in comparison with mostly cloudy locations —LON.30.60° S and LON.30.60° N. Accordingly, the climate conditions are decisive in the middle zone of the room—from 1.5 to 6.0 m.

Finally, addressing the CSA calculation and as deduced from Figure 14B, the impact of the luminance distribution of the sky vault can be lower than the effect of the latitude; a location with predominantly intermediate skies but with a higher latitude—that is to say, a lower average solar elevation—provides an increase of up to 20% toward the rear of the model in comparison with a location with mainly clear skies but placed at a lower latitude—MIL.30.60° S with respect to SEV.30.60° S. This is because CSA measurement is carried out in the vertical plane, unlike the case of DA. Hence, a lower solar elevation—keeping a minimum luminance of the sky vault—can help to provide higher daylight levels.

5. Conclusions

As discussed in the background, the current socio-economic context has promoted telecommuting at home for a noticeable number of workers, although the environment at home is usually not suitable for teleworking since, regardless of the typical limitations in communication, the lighting conditions are not usually adequate for a good performance and for the wellness of users. Therefore, the telecommuting environment must consider not only an appropriate adaptation of electric lighting but also the proper use of natural light for promoting sufficient circadian entrainment. As expressed above, the user's requirements for melatonin suppression vary throughout the day, according to the amount of light and spectra, so electric lighting is not enough to provide a good chronological regulation.

The results obtained serve to describe the suitable scenarios for teleworking, allowing adequate visual comfort and circadian stimulus. These results not only serve to establish design criteria in residential buildings intended for teleworking but also can be useful for dwelling users to find the most appropriate scenario for telecommuting in their houses. As deduced from the results shown in Figures 9 and 12, a window surface equivalent to 10% of the surface of the façade is insufficient to provide minimum circadian entrainment, while proper visual comfort only occurs in the area close to the window. It is necessary to count on a medium-sized window, with an opening façade ratio of 20–30%, to allow sufficient circadian entrainment up to the middle of the room for North orientation and for the entire room for windows facing South. A large window, with an equivalent surface of 40% of the façade, only offers fewer benefits in the zone near the back of the room with respect to a medium-sized window.

As deduced from Figures 10 and 13, the remote obstructions produce a singular effect in the daylight distribution inside the studied room; while any external obstacle reduces the indoor light for South orientation, the reflectance of such obstacle redistributes the light for windows facing North, increasing daylight toward the rear of the model in comparison with a room without remote obstructions. This is particularly true for vertical illuminance values, so the external obstacles can help to promote a good circadian rhythm. Otherwise, the remote obstructions reduce daylight in the horizontal plane, drastically reducing the indoor light toward the rear of the model when the sky fraction is lower than 45°.

Finally, as can be observed in Figures 11 and 12 and subsequently in Figure 14, the climate conditions clearly affect the circadian response and the visual comfort of teleworkers. Accordingly, a mainly cloudy sky scenario requires a large opening, with a window surface equivalent to 40% of the façade, to achieve similar results to those met in a room with a medium-sized window under mainly intermediate or clear skies. It is worth noting that the latitude provides a greater effect on the circadian entrainment than the climate conditions; a location with mainly intermediate skies but at a higher latitude gives an increase of 20% of CSA toward the rear of the model in comparison with a location with a predominance of clear skies but placed at a lower latitude. As observed in a scenario with remote obstructions and a window facing South, the effect of the climate conditions is minimized by the daylight blocking of the outdoor obstacle, although this result is not observed for North orientation, where the externally reflected component mainly depends on the luminance of the sky vault and therefore the climate scenario is key for determining the resulting illuminance both for the circadian entrainment and the visual perception.

These conclusions, as well as the results described above, aim to determine the suitable environment for teleworking rooms, considering the typical parameters of living space for promoting an adequate lighting scenario focused on the comfort and wellness of users.

In the current context, where telecommuting is strongly established in our society, it is worth paying attention to architectural design parameters that can improve our working environment, among which natural lighting results are essential.

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