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Indoor lighting design for healthier workplaces: natural and electric light assessment for suitable circadian stimulus

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Abstract: Light, especially daylight, plays a critical role in human health as the main timer for circadian rhythms. Indoor environments usually lack the correct exposure to daylight and are highly dependent on electric lighting, disrupting the circadian rhythm and compromising the health of occupants. The methodology proposed assesses the combination of natural and electric lighting on circadian rhythms for operational environments. The case study chosen examines a 24/7 laboratory area representing an open-plan shift-work area. Several electric lighting scenarios under different sky conditions have been assessed, considering a variable window size and resulting in a spectrum which establishes the indoor circadian regulation performance according to the amount of light perceived. A set of configurations is presented to determine optimal electric lighting configuration based on natural light conditions in order to ensure a suitable circadian stimulus and the electric lighting flux threshold for different scenarios, benefiting occupants' health while also ensuring energy conservation.

1. Introduction

Glossary

LRC	Lighting Research Center	DA	Daylight Autonomy (%)
ipRGCs	Intrinsically photosensitive ganglion cells	E_{ELE}	Illuminance by electric light (lux)
NSQ	Suprachiasmatic nucleus	E_{DAY}	Illuminance by daylight (lux)
SPD	Spectral Power Distribution	SPD_{ELE}	SPD of electric fixture
CCT	Correlated Color Temperature (K)	SPD_{DAY}	SPD of daylight conditions
CS	Circadian Stimulus	SPD_{REF}	Average spectral reflectance
CL_A	Circadian Light	SPD_{RES}	Resulting SPD

1.1. Background

Nowadays the construction of healthy workspaces is a priority for lawmakers, users and architects with daylight as one of the main variables for its achievement. Daylight has always played a leading role in architecture even when electric lighting was not available [1]. While light is essential in architecture, as it affects spatial recognition, visual tasks, moods and emotional statuses, it also has an effect on circadian rhythms, endogenous cycles which are repeated approximately every 24.3 hours, and their influence on occupants' health [2]. Due to the difference with the 24-hour earth cycle these circadian rhythms need to be synchronized using external signals called Zeitgebers [3] where the main driver is light, especially natural light [4,5].

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Light does not affect the circadian system in the same way as vision [6]. The circadian system, related with the melatonin suppression [7], is more sensitive to short wavelengths whereas the visual sense reacts more to medium wavelengths [8,9]. As a result, the metrics that quantify light impact on both systems are different. For indoor circadian light assessment, the Lighting Research Center (LRC) has developed a mathematical model of phototransduction based on the current knowledge of retina photoreceptors and melatonin night suppression using lights with different spectral power distribution studies [10,11]. This model allows the quantification of the circadian stimulus (CS), expressed as a percentage varying from the activation of melatonin suppression (0%) to its saturation due to the effect of the light perceived (70%). This calculation procedure is based on two main variables, illuminance received by the eye of the observer and the spectral power distribution (SPD) of the light perceived—taking into account that other parameters, such as exposure time, age and pupil diameter of the observer, slightly affect CS quantification.

Phototransduction is needed to develop circadian rhythm regulation. Light is captured by the retina where vision-responsible receptors (cones and rods) are found as well as the main circadian system photoreceptor, the intrinsically photosensitive ganglion cells (ipRGCs), which synthesize a photopigment called melanopsin. In addition to ipRGC photoreceptors, shortwave photoreceptors such as S cones and rods are also involved in phototransduction. Once light has been received by these photoreceptors the stimulus is transmitted along the retinohypothalamic tract to the NSQ, located in the hypothalamus. Phototransduction is a process by which the information collected by photoreceptors is transformed into electrical signals that can be interpreted by the NSQ. These are subsequently sent to the pineal gland, responsible for secreting melatonin, a hormone that controls the sleep cycle. Thus, light exposure causes this hormone secretion inhibition while secretion is produced during dark periods [12,13], with the lowest levels reached during the day and the highest at night [14].

Several studies have quantified light influence on circadian rhythms by establishing optimal CS parameters to ensure a suitable circadian rhythm [15,16]. Figueiro et al. [17] found that workers exposed to light with a high CCT (8000 K) and a CS value of 0.3 had a higher level of circadian rhythm synchronization. In addition, these workers displayed less sleepiness and enjoyed better-quality sleep at night. However, overnight CS levels have to fall below 0.1 to ensure proper rhythm regulation. In these studies, different factors that influence CS values are discussed, most of them focusing on the study of different light sources. Among them, it is worth noting those by Bellia et al. [18].

Daylight is the light source which provides the most suitable quantity, spectrum, timing and duration to entrain our circadian system. It represents the most important resource to provide a suitable circadian entrainment. In accordance with this thought, numerous researchers have studied the influence of the natural light on circadian rhythms [6,11,15,17,19–24]. However, people spend most of their time—almost 90% of the time—indoors [25], where electric lighting dominates. Accordingly, electric lighting should adapt to the needs of the circadian system, promoting melatonin production during the night and melatonin suppression during the day. Nevertheless, fixed emission lighting systems are commonplace in most buildings not linked to the physiological needs of inhabitants, leading to a broad induced disruption of circadian rhythms. Many studies have identified the link between this disruption and a wide array of conditions [21,26–28]. Thus, the long-term health and well-being of the occupants may be compromised by the effects of the indoor environment, especially that of shift-time workers with a higher propension to circadian disruption. To foster better and healthier work environments an accurate and adaptable electric lighting factors management is essential [29,30], not only to ensure adequate vision but also to promote the suitable entrainment of the circadian system.

Although many studies have focused on assessing the effect of natural and electric lighting on the circadian stimulus, most have considered both sources independently [22,31–33], so that they do not reflect actual workspaces in which natural and electric lighting coexist during most of the day, as they do in mid and low latitude areas.

1.2. Aim and objectives

In accordance with the context described above, this paper aims to define an approach for the assessment of open workspaces with different windows orientation located in medium or low latitudes areas with a high daylight availability yearly, where several time-dependent stimulus areas can be found. The purpose of this method is to optimize workspace design both on the electric lighting configurations and windows and indoor distribution to enhance circadian stimulus assuming the integration with daylighting, based on the case study of a 24/7 laboratory. Electric lighting configurations have been determined under different natural light scenario conditions, ensuring that a minimum CS value is reached throughout the entire room considering the blend of both light sources. The target objective is based on two Correlated Color Temperatures (CCT) and on six luminous fluxes for the electric fixtures, while three different sky conditions throughout the year are considered.

The novelty of this research lies in the calculation of the circadian stimulus considering both the electric and the natural source, to set up luminous flux by electric lighting in accordance with different SPD combinations.

The conclusions of this study provide a new methodological approach for the configuration of electric lighting based on the architectural design, as well as on the benefits in the circadian stimulus resulting from an enhanced use of daylighting and management.

2. Methods

The study relies on previously established methodologies such as [22,33,34] to assess the integrated effect of natural and electric lighting.

2.1. Characteristics of the room model

A 24/7 hospital laboratory area is chosen, in this case within a central main health facility in the city of Seville (Spain) (see Fig. 1). It is a continued shift-work activity area where workers need to maintain a high level of alertness in task performance. As the room configuration shows great similarities to typical open plan workspaces, the methodology can be easily replicated in many work centers, including common areas in offices and call centers.

Fig. 1. 24 – hour laboratory area of the Virgen del Rocío University Hospital (HUVR)

The laboratory area is located in Seville (Spain), with a latitude of 37° 21’ 42’’ and a longitude of 5° 58’ 50’’. It is located on the fourth floor of the laboratory building, 13 m from the ground. The building is in a hospital complex where the roads are wide for the cars, ambulances, or tracks so the closest buildings do not cast shadows on the study object. It should also be noted that there are trees in the streets but being a fourth floor, they do not represent an obstruction. Another important issue to be considered is the ground reflectance which is 0.20. The laboratory has dimensions of 13 m x 15 m and a free height of 2.70 m. It has two opposing façades with the same fenestration distribution, north and south orientation, and an azimuth of 145’26° in winter and 103’58° in summer. Horizontal sliding windows measure 1.36 m x 1.75 m, with a visible transmittance of 0.78. The different room surfaces have been characterized by means of a spectrophotometer (PCE-CSM 8) obtaining the following reflectance values per wavelength, shown in Fig. 2.

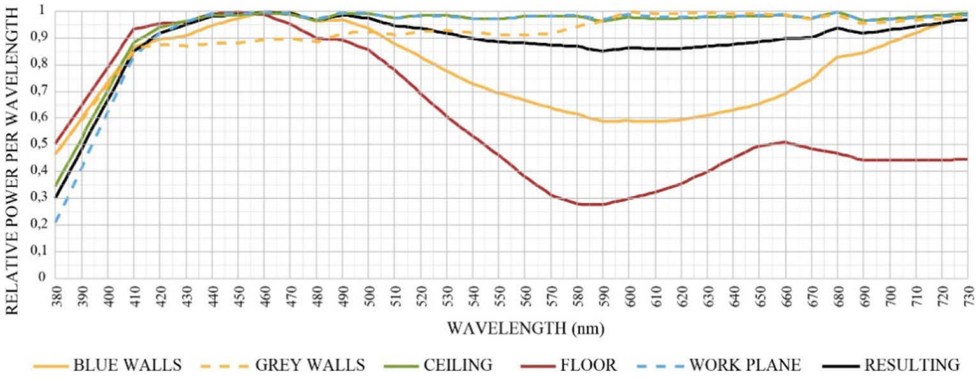

Fig. 2. Room surface reflectance.

This research assumes that the resulting spectra received in the eye of the observer—resulting value, which serves to quantify the CS, depends on the reflectance of the inner surfaces in accordance with the subtended angle of vision and their surface area, as in Bellia et al. [24]. The following influence percentage has been estimated: 30% for walls, 10% ceiling, 10% floor and 50% work plane.

2.2. *Selecting daylight conditions*

Light affects circadian rhythms depending on the illuminance and the SPD received through the eyes. The first parameter, illuminance, depends on windows size, orientation, glass transmittance, sky conditions and sun position which depends on the date (hour and day of the year). The second factor, the light source SPD, is based on the sky conditions and window orientation. It must be noted that, following the demonstration of Laura et al. [24], the slight variation of the daylight SPD barely affects to the circadian response, being more decisive the amount of light perceived by the eyes of the observer. Despite the minimal influence of the sky SPD, it is taken into account in order to provide more accurate results.

2.2.1. Time

The impact of daylight on circadian rhythms was assessed throughout the year. As dynamic metrics are calculated considering the statistical weather conditions throughout the whole year, a specific SPD for daylight cannot be used, given that the results provided by Daylight Autonomy (DA) do not refer to a specific time or sky condition. Accordingly, the illuminance value was quantified for a specific time and SPD, described in the sub-section below. In the case of daytime, 11 am was selected since although melatonin suppression starts early in the morning, the lowest levels are achieved around 11 am. The objective of the calculation procedure is to provide enough melatonin suppression (about 30%) in a critical period of the cycle (11 am). This procedure is based in those carried out by previous researches [17,22,24,34]. In this case study, the 24-hour laboratory, the workers shifts are from 8 am to 8 pm and from 8 pm to 8 am. Therefore, lighting requirements during the night are assessed to achieve a melatonin suppression of 30% at 11pm.

2.2.2. Sky conditions and window orientation

Three different sky conditions were selected to encompass typical conditions in the location area: clear sky, overcast sky and an intermediate one. Even though only one sky type can be chosen for each calculation model, the sun position causes the daylight SPD to change depending on window orientation. As bilateral windows do not provide the same natural light SPD the following hypotheses were used:

- Clear sky (CIE12): the SPD of CIE D50 to light entering through south-facing windows and CIE D65 to light entering through north-facing windows.
- Intermediate (CIE 7): the SPD of CIE D50 to light entering through south-facing windows and CIE D55 to light entering through north-facing windows.
- Overcast sky (CIE 1): the SPD of CIE D50 to light entering through south- and north-facing windows.

The assumption presented for daylight spectrums corresponds to average SPD deduced from the real measurements obtained in the laboratory case study. It should be noted that the SPD of the sky can vary slightly depending on the time, modifying the resulting CCT. However, as in previous research [24,34], variation of the sky SPD between 5500 and 6500 K barely affects circadian stimulus, since the spectral distribution is remarkably similar. The three different SPDs used are shown in Fig. 3.

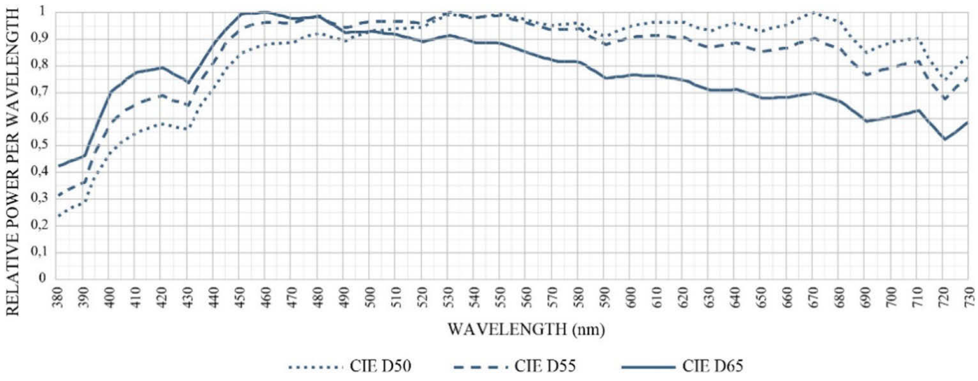

Fig. 3. Natural light spectral power distribution.

2.2.3. Window size

Three different room models with different window sizes were defined to evaluate the effect of window-to-façade ratio. In the first room model—which corresponds geometrically to the real one—windows occupy 20% of the façade surface, while in the second room models grow to 30% of the façade surface and to 40% in the third model. Table 1 features characteristics of the room model.

2.3. Selecting electric light conditions

The circadian entrainment depends up to 70% on the amount of light and spectra, so the ability of daylight to promote a good circadian stimulus is limited in any case. In addition, electric

Table 1. Room model window features.

Material	Window-to-façade ratio	Surface (m^2)	Dimensions (m)	Glass surface (m^2)	Glass surface/total surface	Visual transmittance
Model 1	20%	2.38	1.36 × 1.75	1.41	0.59	0.78
Model 2	30%	3.14	1.65 × 1.9	2.8	0.89	0.78
Model 3	40%	3.61	1.9 × 1.9	3.24	0.897	0.78

lighting use to provide a poorer circadian response than the natural source, due to the static spectra of this light source. Although electric lighting effect is more limited, it is a basic need in indoor spaces. Two scenarios were used to analyze the effect of natural and electric lighting on circadian rhythms: one with warm LED lamps, with a Correlated Color Temperature (CCT) of 2700 K and another with cool LED lamps and a CCT of 5700 K corresponding to typical commercial fixtures. The SPD for each electric light source and their photometry are shown in Fig. 4. The used photometry corresponds to troffer luminaires, the most typical luminance distribution used in open workspaces. It should be highlighted that, although there are other characteristics such as the luminous flux more relevant, the photometry can produce a variation of the resulting illuminance, modifying the CS values.

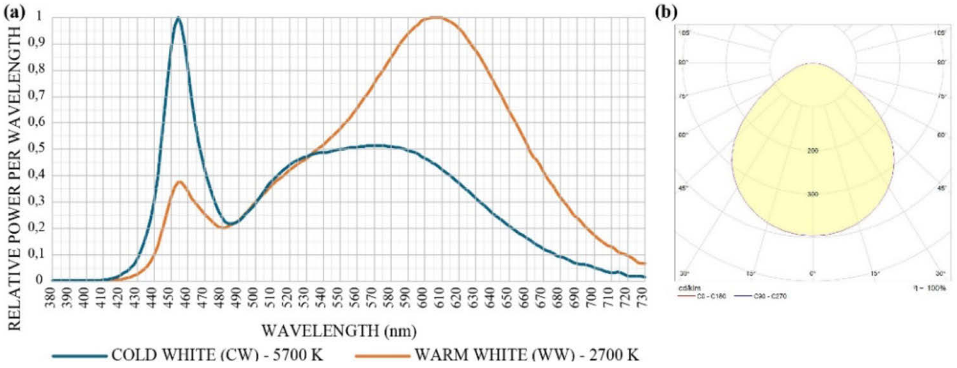

Fig. 4. (a) Electric lighting spectral power distribution. (b) Electrical lighting photometry

Furthermore, the effect of different light fluxes was assessed in each of these scenarios. Commercial standardized light luminous fluxes of 2200 lm, 2500 lm, 3200 lm, 3400 lm, 3600 lm and 4100 lm were selected. They provide a mean illuminance in the workplane of 320 lx, 363 lx, 465 lx, 494 lx, 523 lx and 596 lx respectively. The lighting fixture distribution is an almost perfect grid with the luminaires 2.4 m apart. Fig. 5 shows the electric lighting arrangement of the laboratory case study.

Considering natural and electric lighting scenarios, 831 analysis models were developed (63 considering daylight alone, 12 with electric light alone and 756 models with mixed light sources). All these models (831) are represented in Fig. 6. This shows the variable parameters which produce the different combinations. It should be noted that the spectral combination of natural and electric light is carried out depending on the amount of light provided by both sources according to each study point. Therefore, the closer the study point is to the window, the higher the influence of daylight spectra.

2.4. Metrics

A virtual model of the laboratory was built and simulations performed to achieve the results of the illuminance and CS metrics. Illuminance was assessed both in the horizontal plane to

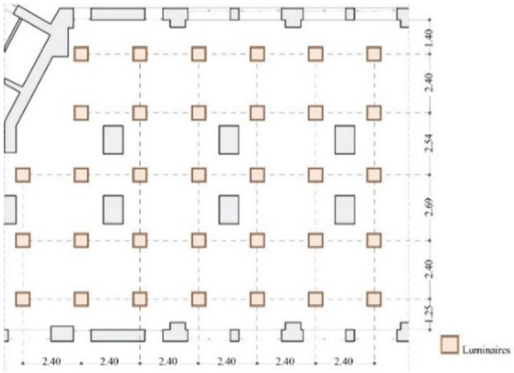

Fig. 5. Electric lighting fixture distribution.

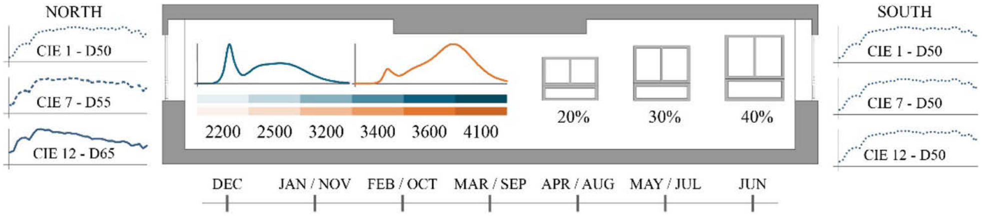

Fig. 6. Calculation models considering the mix of natural and electric lighting.

identify the light effect on the visual system and in the vertical plane to determine CS values. Average illuminance provided by electric lighting systems was established using the DIALux tool, validated as accurate for electric lighting [35]. The average illuminance supplied by daylight was calculated using the daylight simulation program Daylight Visualizer whose accuracy and validity have been demonstrated in several studies [36,37]. In addition, the laboratory case study was used to compare the illuminance measures under real sky conditions with those observed in the simulation model, endorsing the accuracy of the calculation programs.

As described in the background, CS is the metric developed by the LRC to measure melatonin suppression caused by light. It was calculated using Eq. (1) in which the circadian light (CL_A) is determined using Rea et al.'s model of human phototransduction [10] from the source spectral power distribution and the illuminance values obtained in the study points.

CL_A depends mainly on the SPD and the illuminance perceived through the eye. Therefore, both parameters must be measured in the vertical plane, in accordance with the theoretical position of the observer.

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

2.5. Selecting study points

Both metrics described above were assessed in the study points shown in Fig. 7. A mesh with a 1 metre discretization in one direction and 2 metres in the perpendicular axis was created in the room model. Different heights were considered for the study points in order to assess the metrics mentioned above. Horizontal illuminance was calculated at a work plane height of 0.90 metres—laboratory desk height—whereas vertical illuminance and CS values were measured at eye level for a person standing, 1.55 metres. In the vertical calculation plane values are measured in four different directions, towards the two facades with the windows and towards the opposites, to ensure a good CS in every user's position. This is because horizontal illuminance is measured to guarantee good visual comfort with suitable work plane illumination while CS values must be measured at eye height as laboratory staff work standing up most of the time.

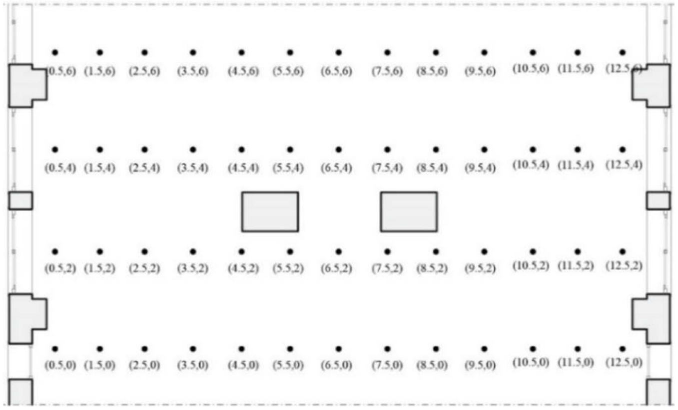

Fig. 7. Calculation array of the room model for lighting metrics.

2.6. Calculation process

The calculation procedure is based on the quantification of the main parameters which determine the CS value: the resulting SPD and the illuminance received through the observer's eye. Both parameters are determined following the procedure described below:

1. Illuminance provided by electric and natural light is calculated for every reference point separately, using the DIALux and Daylight Visualizer programs, as described above.
2. The resulting SPD of electric and natural light sources is calculated considering the SPD sources defined in Figs. 3 and 4 and the spectral reflectance of the environment, established in Fig. 2.
3. The resulting SPDs previously defined are combined based on the illuminance determined in each point.
4. CL_A is calculated according to the combined SPD and illuminance provided by electric and natural light sources.

The procedure described can be summarized as Eq. (2):

$$fSPD_{RES}(\lambda)_{380}^{730} = \frac{E_{DAY}}{E_T} fSPD_{DAY}(\lambda)_{380}^{730} \cdot fSPD_{REF}(\lambda)_{380}^{730} + \frac{E_{ELE}}{E_T} fSPD_{ELE}(\lambda)_{380}^{730} \cdot fSPD_{REF}(\lambda)_{380}^{730} \tag{2}$$

where SPD_{RES} represents the resulting SPD received by the observer's eye, E_{DAY} is the illuminance provided by daylight source, E_{ELE} is the illuminance given by electric light, E_T is the total amount of illuminance perceived, SPD_{DAY} corresponds to the SPD of daylight conditions, SPD_{ELE} is the selected SPD for the electric fixture, and SPD_{REF} is the average spectral reflectance of the environment.

According to the procedure described, Fig. 8 shows a calculation example of SPD combination provided by electric and natural light.

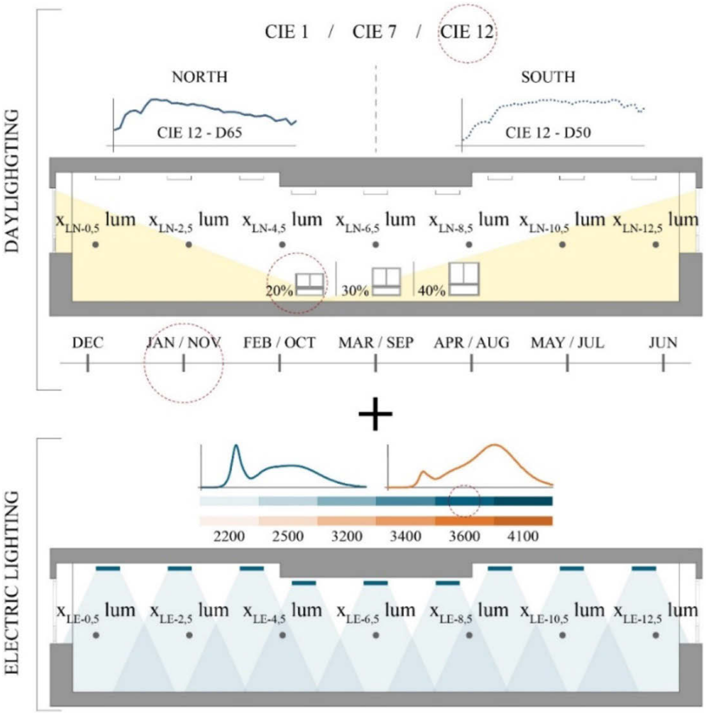

Fig. 8. Scheme of CS calculation considering natural and electric lighting.

3. Results

3.1. Average circadian stimulus promoted by daylighting

According to the previous methodology, CS values were calculated at each array point considering the variables defined and represented in Fig. 9. In every laboratory cross-section the average CS—ranging from 0 to 70%—was defined in the vertical axis. Results are shown according to three different sky conditions—overcast (CIE 1), intermediate (CIE 7) and clear (CIE 12)—defining CS values for 11 a.m. for solstices. It should be noted that these calculations were carried out for every month throughout the year, although for the sake of brevity only the most representative days are shown. The minimum CS level of 0.3 to promote a suitable circadian rhythm [17] is referenced in the graphs. Room zones near the façades where there is enough natural light to provide a CS value equal or higher than 0.3 are represented by orange bars, while pale blue bars determine where electric lighting is required, complementing daylighting.

As expected, the highest CS scores were near the windows, higher in the south orientation than in north, deducing that the closer to the center of the room the lower the CS values. The most favorable scenario takes place in summer with a clear sky and a window-to-façade ratio of 40% where 70% of the laboratory area does not require electric lighting (at 11.00 a.m.). Otherwise, the worst value is in winter with an overcast sky and a 20% window-to-façade ratio when only 2.3% of the area receives enough natural light to achieve a CS of 0.3. Table 2 shows the distance from the façade where CS is enough thanks to daylight alone.

3.1.1. Season of the year and sky conditions

As deduced from Fig. 9 and Table 2, the season of the year is a decisive parameter for determining the CS value, as the higher the daylight illuminance, the lower the relevance of the spectral

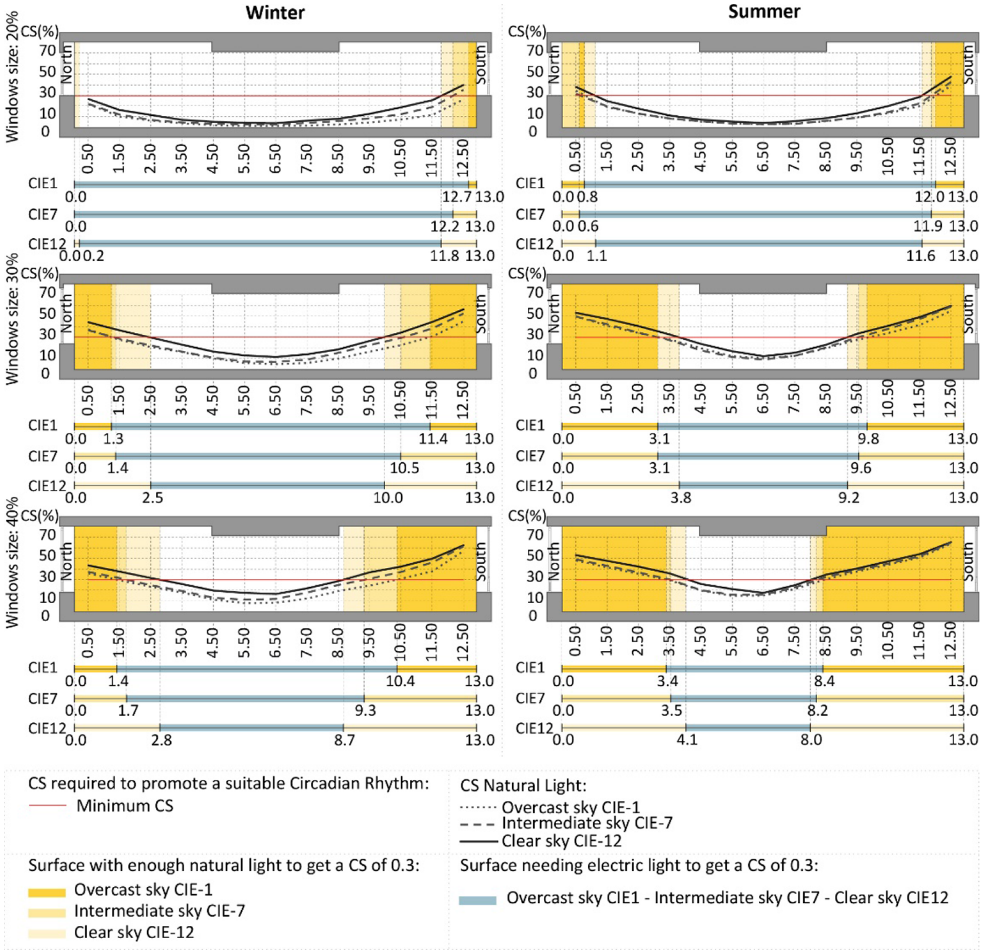

Fig. 9. CS value variation by room depth for daylight only.

Table 2. Distance from the façade where a suitable CS value is obtained by daylight alone, according to a Seville location at 11 am

Year season	Window ratio	Distance from the façade (m)								
		North			South			Total		
		CIE1	CIE7	CIE12	CIE1	CIE7	CIE12	CIE1	CIE7	CIE12
Winter	20%	0.0	0.0	0.2	0.3	0.8	1.2	0.3	0.8	1.4
	30%	1.3	1.4	2.5	1.6	2.5	3.0	2.9	3.9	5.5
	40%	1.4	1.7	2.8	2.6	3.7	4.3	4.0	5.4	7.1
Autumn - Spring	20%	0.4	0.3	0.8	0.7	1.2	1.5	1.1	1.5	2.3
	30%	2.4	2.3	3.4	2.4	3.2	3.7	4.8	5.5	7.1
	40%	2.5	2.9	3.7	3.7	4.6	5.1	6.2	7.5	8.8
Summer	20%	0.8	0.6	1.1	1.0	1.1	1.4	1.8	1.7	2.5
	30%	3.1	3.1	3.8	3.2	3.4	3.8	6.3	6.5	7.6
	40%	3.4	3.5	4.1	4.6	4.8	5.0	8.0	8.3	9.1

distribution of the sky conditions. This assertion can be deduced from the room sections in summer, where the distance from the façade which reaches a suitable CS value is similar, irrespective of the assumed SPD of the sky. In winter, the lower daylight illuminance implies a more relevant role of the light spectra, defining an adequate CS value according to both the external illuminance and its spectra.

As seen in Table 2, an adequate CS value is difficult to obtain during the winter season throughout practically the entire laboratory area. This situation can improve in the intermediate seasons, reaching its maximum value with clear skies during the summer. In all scenarios a significant fraction of the work area displays insufficient stimulus and requires electric lighting to be switched on.

In the room area near the south-facing windows, CS values at the equinoxes and summer solstice are very similar, with an increase for summer of only 4% in the case of the smallest windows. As deduced from Fig. 9, the larger the window-to-façade ratio, the closer the CS values between middle-season and summer, showing a difference of only 2%. However, during the winter season, CS values are around 20% lower than at the equinoxes or the summer solstice with a window ratio of 20% despite the fact that CS levels edge closer together as window size increases, so that the difference is reduced to 7%.

In the room area near the north façade the CS values reached in every season of the year season do not match up. In the 20% window-to-façade ratio configuration the CS level is 21% lower in winter than at the equinoxes, observing a 14% increase from spring equinox to summer. When the window ratio increases to 40%, the difference between seasons decreases to 15% between winter and equinoxes and 9% from equinoxes to summer. In both the south and north façades, the influence of the seasons on CS values decreases as the window-to-façade ratio increases. Otherwise, as deduced from Table 2, in the center of the room the larger the windows, the higher the season influence on CS levels.

3.1.2. Window size

As is to be expected, the higher CS values are reached with the larger windows. However, this does not imply a linear tendency of the CS values. As seen in Fig. 9, a small opening size—window-to-façade ratio of 20%—does not allow sufficient circadian response, irrespective of the weather conditions or the season of the year. Moreover, the medium-sized window results in adequate melatonin suppression in the zone near the façade—specifically 3 m, which is equivalent to the lintel height—, irrespective of sky SPD or window orientation. Finally, the largest window—window-to-façade ratio of 40%—increases the room area with a sufficient CS value, about 50% compared to the medium-sized window, that is to say, approximately one and a half times the height of the lintel. This increase is slightly lower when daylight illuminance is high enough, as in the case in summer, but the previous assertion establishes a rule of thumb for designers wishing to consider a proper use of daylighting to promote good circadian entrainment.

3.2. *Average circadian stimulus promoted by the combination of natural and electric lighting*

Figure 10 shows CS values produced by both natural and electric lighting, with three different luminous fluxes—2200 lm, 3200 lm and 4100 lm—and cool/warm luminaires (5700/2700 K). As deduced from Fig. 10, cool LED lamps (CCT 5500K) provide higher CS levels than warm LED lamps (CCT 3500 K), given that cool light sources have a higher SPD in the short-wavelength range than that observed for warm sources, stimulating the melatonin suppression. This is emphasized in the middle of the room, where daylight influence is lower than electric lighting. For comparison, cool luminaries with a luminous flux of 2200 lm provide higher CS values than warm ones with a higher luminous flux of 4100 lm. On average, 5500 K sources promote CS values 40% higher than warm fixtures in any season for the central room area—where natural

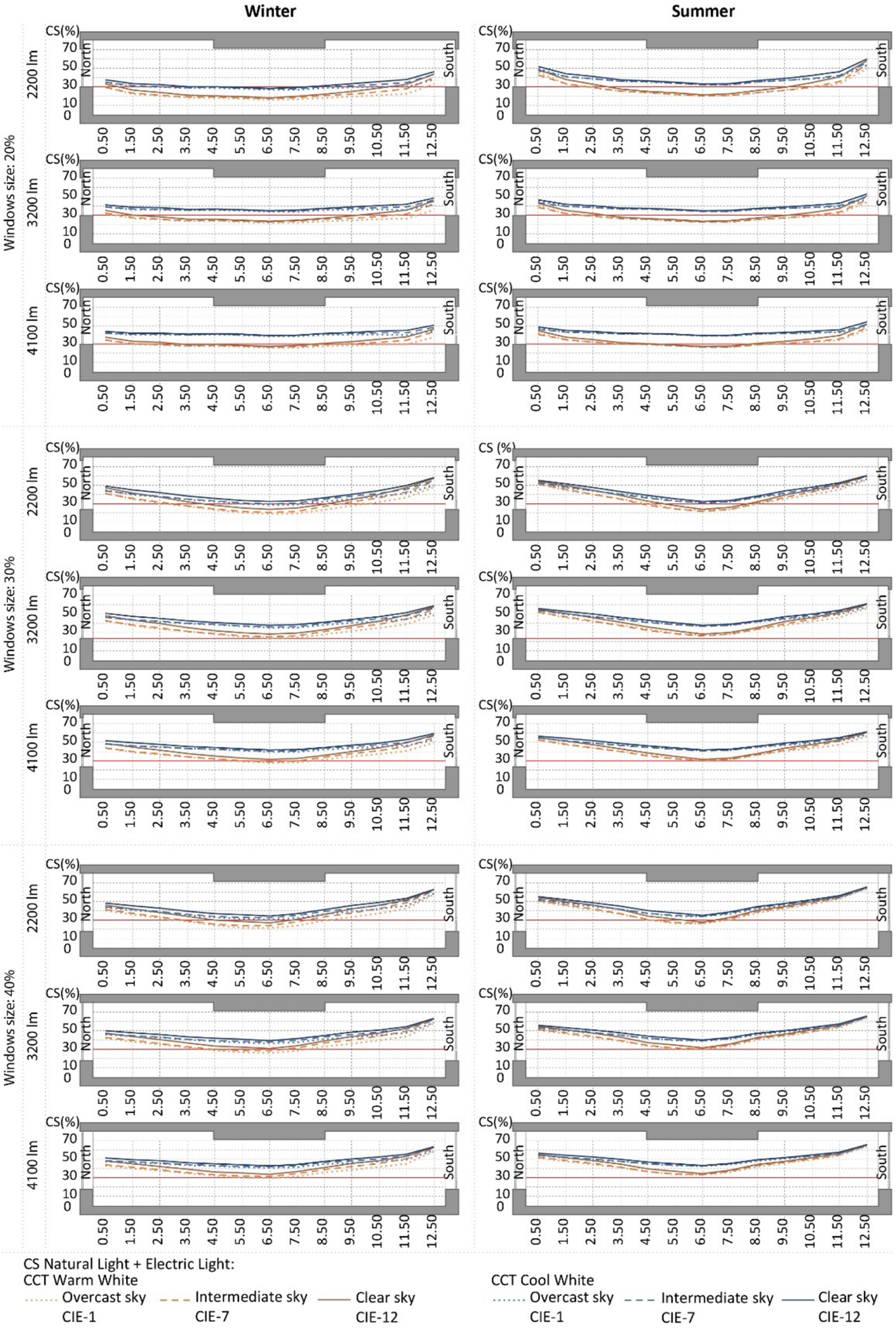

Fig. 10. Circadian stimulus promoted by the combination of natural and electric lighting.

light influence is negligible. Although the difference between CS levels provided by cool and warm lamps in every season is practically the same, this not the case with window size. The greater the window-to-façade ratio, the lower the difference between cool and warm sources, with CS levels promoted by cool lamps 50% higher than those by warm lamps in the case of small windows, 36% higher for medium-sized windows and 29% higher considering large windows. As expected, larger windows provide a better use of daylight and accordingly a lower dependence on electric lighting, irrespective of the spectral distribution of the sky.

3.3. *Average circadian stimulus promoted by electric lighting*

Despite carrying out the study at 11 am to ensure adequate suppression of melatonin in the dayshift, the assessment of the night scenario of only-electric-lighting is developed since the case study is a 24-hour workspace. Figure 11 shows the circadian stimulus caused by each electric light source so that the suitable luminous flux could be chosen to achieve the appropriate CS. As it can be seen, with a warm white electric lighting source a minimum luminous flux of 4100 lm is required to achieve a 0.3 CS value in every point of the workspace. This minimum luminous flux get lower with a cool white luminaire since 3200 lm are sufficient to provide a good CS. It should be noted that the electric lighting configuration during the night cannot be static since the circadian stimulation needs var throughout the shift. Therefore, these luminous fluxes of electric lighting are suitable to provide a CS of 0.3 around 11 pm, as explained in the methodology.

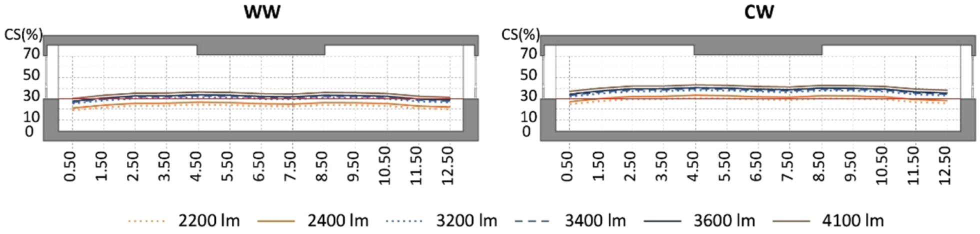

Fig. 11. Circadian stimulus provided by electric lighting.

4. Discussion

The results observed above serve to determine guidelines to quantify the luminous flux required both to guarantee a minimum illuminance value for visual tasks and to provide a suitable CS value for occupants. This section quantifies the luminous flux of the fixtures, considering the variables described in the methods—window size, distance from the façade, sky conditions and CCT of electric lighting.

In order to ensure a proper visual performance, a minimum illuminance level of 500 lx in the work plane is set as the priority target. Therefore, the minimum luminous flux was also deduced to achieve this target as defined in UNE –EN 12464-1. Based on the calculation of CS levels promoted by natural and electric lighting in each of the previous scenarios, the minimum luminous flux resulting in a CS of 0.3 was calculated monthly throughout the year following the parameters of luminaire color temperature, sky conditions and window-to-façade ratio. Since electric lighting needs differ at every study point the room was divided into two control zones, and values measured at a representative calculation point in each of them has been used.

Furthermore, the results are shown in Fig. 12, where the horizontal axis represents the months of the year while the vertical one defines the minimum luminous flux required. It should be noted that the lighting requirement for providing suitable CS values are usually different from those required for the visual needs and are lower for cool lamps and higher for warm luminaires. It must be also highlighted that while the illuminance threshold for providing a CS value is measured in the vertical plane, the illuminance requirements for visual needs are considered in the horizontal work plane.

As in Fig. 12, the analysis can be carried out in two different ways, comparing the minimum luminous fluxes required to achieve a minimum illuminance level of 500 lx at work plane with the minimum ones needed to obtain a CS level equal to or higher than 0.3, either with cool or warm luminaires, and comparing the variation of the minimum necessary flux throughout the year in each scenario. Furthermore, this analysis must be carried out allowing for the laboratory position.

4.1. Comparison of minimum flux required to achieve 500 lx or a CS level of 0.3

As shown in Fig. 12, the amount of luminous flux produced by cool lamps to achieve sufficient illuminance for task requirements—defined as 500 lx—is always higher than that needed to provide a good CS. Therefore, it can be stated that cool lighting fixtures which provide sufficient illuminance for task requirements also give a suitable CS level. In contrast, in all instances warm lamps require a luminous flux higher than that needed to guarantee the task requirements, in order to ensure an appropriate CS value.

Window size affects the luminous flux demanded by the lighting fixtures, as it determines the use of daylight. As deduced from Fig. 12, the lower the window-to-façade ratio, the higher the difference between the luminous flux required for cool and warm lamps. In addition, the luminous flux demanded throughout the year is more stable considering a small window size.

It can be also noted that the divergence between the luminous fluxes required for cool and warm lamps to provide sufficient CS decreases when the window size is larger and therefore the use of daylight is also higher.

4.2. Comparison between minimum flux required in each scenario throughout the year

As can be deduced from Fig. 12, the luminous flux demanded for the electric fixtures varies according to each daylight scenario—overcast, intermediate and clear—and throughout the year, in accordance with the daylight illuminance provided by the sky. An analysis can be carried out considering each study point:

- In the room center:

Considering overcast sky conditions, a higher luminous flux is required at the winter solstice, decreasing as the summer solstice approaches in most of the scenarios studied. This tendency varies in the cases with an intermediate or clear sky. In these scenarios the required luminous flux decreases from winter to the equinoxes but increases as summer approaches. Considering a clear sky, requirements in summer are even higher than in winter due to the sun trajectory. In all different sky scenarios, the larger the windows, the greater the difference between the minimum required luminous flux in every month of the year.

- Near the windows:

As seen in Fig. 12, electric lighting is not required in many months of the year considering a window-to-façade ratio of 30%. Another main difference with regard to the previous study point is that in all scenarios the luminous fluxes needed are greater at winter solstice and always decrease as summer approaches. Finally, as deduced from Fig. 12, the higher the window-to-façade ratio, the greater the difference between the minimum luminous fluxes required in the solstices, with a difference of only about 200 lm between both scenarios with a small window and around 2600 lm with a large opening.

Results obtained in Fig. 12 highlight that the needs for electrical lighting are not the same throughout the whole room and therefore each luminaire line requires a daylight-linked control. Accordingly, Fig. 13 has been designed in order to propose electric lighting configurations for each scenario. Each laboratory section shows 3 areas defined with different luminaire regulations, according to the electric luminous flux required to meet a sufficient CS value higher than 0.30.

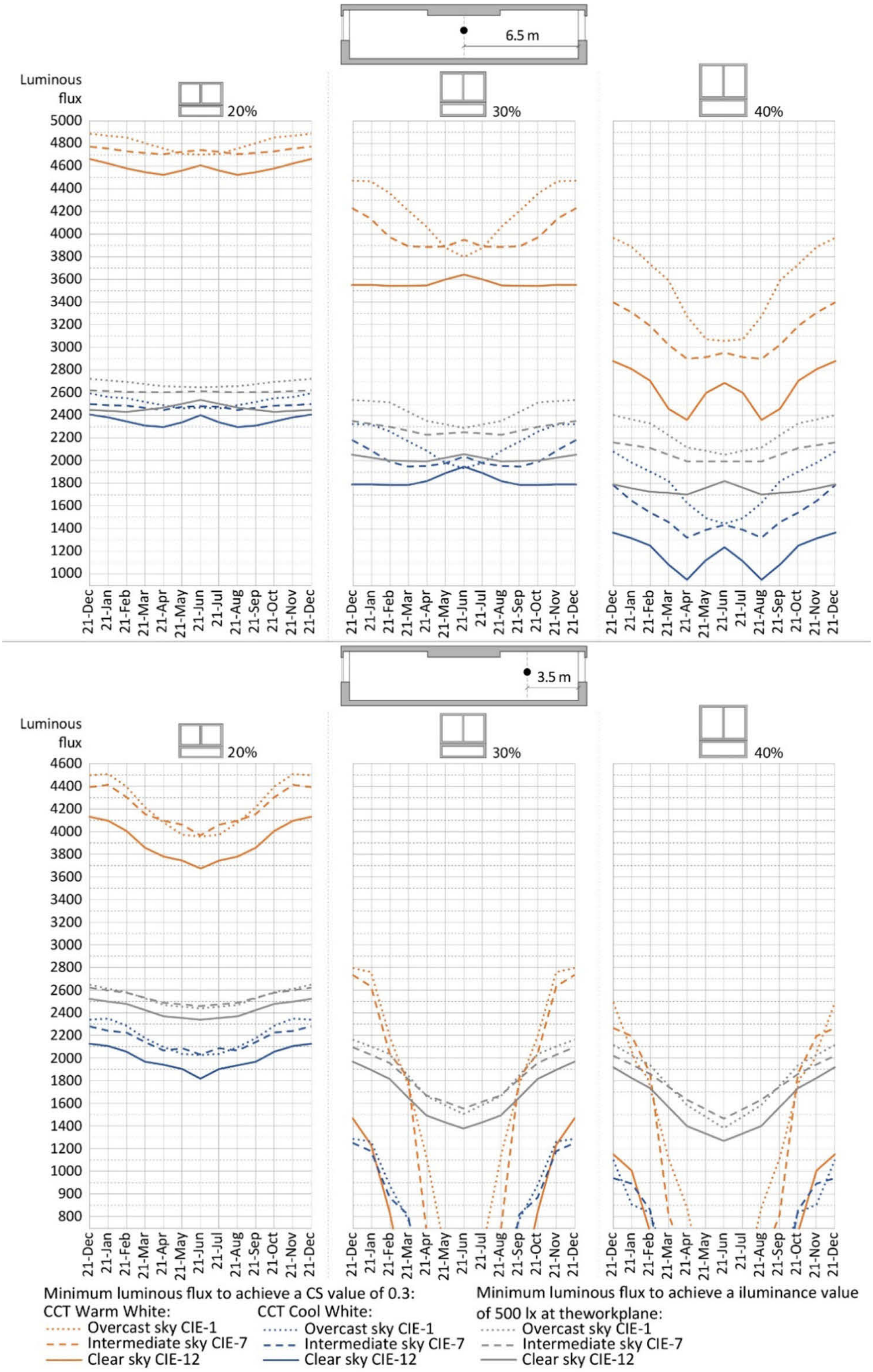

Fig. 12. Minimum luminous flux (lm) to ensure a CS of 0.3 and an illuminance of 500 lx.

Ten steps are defined in order to represent the demanded luminous flux according to cool and warm lamps. The vertical axis determines the CS quantification, while the horizontal one corresponds to the distance from the North façade. As deduced from Fig. 13, the luminous flux required under winter conditions varies from 1500 lm to 4500 lm with warm lamps and between 300 lm and 2400 lm with cool lamps. These values increase in the room center: 3500 lm and 5000 lm with warm sources and between 1800 lm and 2700 lm with the cool ones. Otherwise, considering the summer scenario, the electric luminous flux corresponds to 4000 lm with warm lamps and 2100 lm with cool lamps in the zone near the windows, while these values rise up to 5000 lm with warm lamps and to 2700 lm with cool lamps in the center of the room.

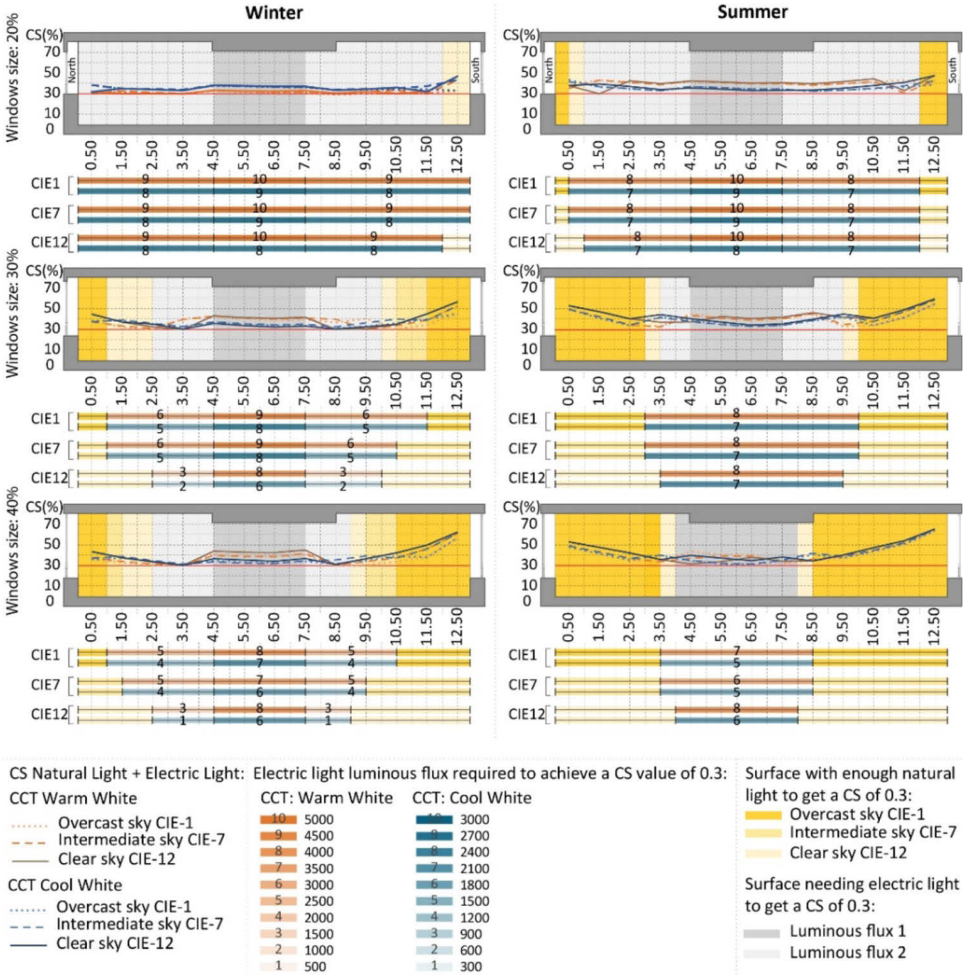

Fig. 13. Electric lighting configuration. Circadian stimulus promoted by both natural and electric lighting.

5. Conclusions

Providing healthy indoor environments should be a must for building designers and ensuring an appropriate circadian rhythm synchronization through lighting is one of the most influential factors for real long-term well-being. Therefore, a methodology was developed to allow the integration of natural and electric light in the evaluation of an adequate circadian stimulation of the occupants in lighting design. This procedure can be exported to other scenarios, with different boundary conditions, such us the climate conditions, different luminaries' type or the architectural configuration. Through this process, a lighting outline guideline was proposed, which can be adapted to different configurations of windows, orientations, locations, room size and light performance. Although lighting regulation should be studied throughout the day, this study focuses on establishing a lighting configuration at the critical moment for a maximum effect on the regulation of the circadian rhythm. Despite this, the developed methodology could be applied at any other time of the day.

A dynamic and adaptive control of electric lighting is a key aspect for ensuring occupants' well-being in the indoor environment—where exposure to natural light is not usually sufficient to promote an appropriate circadian rhythm. This research provides design guidelines for a suitable CS promotion when integrating daylighting and electric lighting. Figures 12 and 13 show example tools that can be extrapolated to similar spaces, helping not only to determine luminous flux but also to optimize electric lighting through a configuration adaptable to outdoor environment conditions. In offices, laboratories and other open spaces with similar characteristics, electric lighting configuration must be capable of varying its luminous flux between two yearly thresholds (maximum in winter and minimum in summer) in order to promote adequate circadian entrainment while ensuring task lighting. The results obtained are strongly dependent on CCT with a fluctuation range between 3000 lm and 5000 lm with warm lamps and between 1500 lm to 2700 lm with cool lamps for the case study. The specific fluctuation ranges vary—between the maximum and minimum values—in accordance with the position of the observer with respect to the window. Thresholds also change depending on window size, so window-to-façade ratio is one of the critical aspects to be considered when setting up electric lighting.

The picture emerging from the results obtained also shows conclusions that can be adopted in similar scenarios. As deduced from Fig. 12, the luminous flux provided by cool lamps to meet 500 lx as a task requirement is also enough to provide sufficient circadian entrainment. In contrast, in all cases warm lamps require a luminous flux higher than 500 lx to guarantee an appropriate CS value. Moreover, as deduced from Fig. 9 and Table 2, the higher the daylight illuminance, the lower the relevance of the spectral distribution of the sky conditions, so that solar altitude and outdoor lighting are more decisive than the sky SPD. In winter, lower daylight illuminance implies a more relevant role of the light spectra.

As observed in the results, there is no linear tendency of the CS values according to window size. As deduced from Fig. 9, a small opening size does not provide a sufficient circadian response, irrespective of the season of year. Otherwise, the medium-sized window produces an appropriate melatonin suppression near the façade—approximately at the height of the lintel—, regardless of sky spectra or window orientation. Finally, the largest window increases the room area with a sufficient CS value by about 50% compared to the medium-sized window, that is to say, approximately one and a half times the height of the lintel. This increase is slightly lower in summer, but as expressed in the analysis, the previous assertion establishes a rule of thumb for designers who wish to consider a proper use of daylighting to promote good circadian entrainment.

Finally, as anticipated in the introduction, electric lighting optimization also contribute to energy conservation while ensuring the welfare conditions of the users. Comparing the proposed adaptive lighting configuration with a static one, the following assessment must be noted regarding to energy savings. This regulable configuration causes energy savings in summer of 21% in the worst-case and up to 80% in the most favorable scenario. In winter, energy savings are lower due to a greater electric lighting dependance, even so, energy savings of up to 60% can be achieved in the most favorable situation.

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