Analysis of circadian stimulus allowed by daylighting in hospital rooms

*Ignacio Acosta, Instituto Universitario de Arquitectura y Ciencias de la Construcción, Universidad de Sevilla
Russell Leslie, Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York, USA
Mariana G. Figueiro, Lighting Research Center, Rensselaer Polytechnic Institute, Troy, New York, USA

Corresponding author:
Ignacio Acosta
Instituto Universitario de Arquitectura y Ciencias de la Construcción
Universidad de Sevilla, 41012 Seville, Spain
Tel.: 0034647550654
Email: iacosta@us.es

Abstract

Light is the major synchronizer of circadian rhythms to the 24-hour solar day. Compared to the visual system, the circadian system requires more light to be activated and is more sensitive to short-wavelength light. Without access to daylight, or electric lighting providing comparable amount, spectrum, distribution, duration, and timing, human health and wellbeing may be compromised. This may be particularly true for those confined indoors, such as patients in hospitals and residents in eldercare facilities. Architectural and design features, including window size, surface reflectances and furniture placement, impact circadian stimulus levels. The present paper details results of simulations used to determine percentage of days that patients would receive a minimum level of circadian stimulation as a function of different window-to-façade ratios, surface reflectances, and latitudes.

Keywords: circadian stimulus, daylighting, window, lighting simulation, hospital

1. Background

Window design is the key element for allowing daylight inside buildings[1] and a proper design can improve thermal comfort and save electric lighting energy.[2] Research efforts have investigated how windows provide daylight in a space in terms of the light distribution and potential lighting energy savings.[3, 4] Other studies evaluated shading devices,[5, 6] defining the effect of blinds or overhangs on daylight availability inside buildings, as well as the relationship of these shading devices with electric lighting.[7] Recent studies have also examined the relationship between daylighting and health outcomes.[8, 9] In addition to enabling us to see, light reaching the retina has a profound effect on human health and wellbeing via its impact on our circadian rhythms that regulate sleep, mood, and alertness. Circadian disruption is associated with long-term health risks, including diabetes, obesity, cardiovascular disease, and cancer.[10-12] Light is the major synchronizer of circadian rhythms to the Earth's 24-hour light-dark cycle. Circadian rhythms in humans, such as the sleep-wake cycle, repeat approximately every 24 hours. In the absence of any external cue, human circadian rhythms run with an average period slightly greater than 24 hours (approximately 24.2 hours). Morning light resets the biological clock daily and promotes entrainment to local time on Earth.

Lighting characteristics affecting vision differ from those affecting the circadian system. The circadian system, as measured by acute melatonin suppression, is maximally sensitive to short-wavelength (blue) light, with a peak spectral sensitivity at around 460 nanometers (nm), while the visual system, as measured by visual acuity, is most sensitive to the middle-wavelength portion of the visible spectrum, peaking at around 555 nm.[13-15] The circadian system is dependent on the timing of light exposure. Light that is applied before the minimum core body temperature, which is reached approximately 1.5 to 2.5 hours before one naturally awakens, will delay the clock, resulting in later bedtimes and wake times the following day. Light applied after minimum core body temperature is reached will advance the clock, resulting in earlier bedtimes and wake times the following day.[16] While the visual system responds to a light stimulus very quickly (in milliseconds), the duration of light exposure needed to affect the circadian system can take several minutes. It is also important to note that the short-term history of light exposure affects the sensitivity of the circadian system to light; the higher the exposure to light during the day, the lower the sensitivity of the circadian system to light, as measured by nocturnal melatonin suppression and phase shifting.[17]

Daylight is arguably the ideal light source for synchronizing the human circadian system, providing the right amount, spectrum, distribution, duration, and timing needed for entrainment to local time. Indeed, for millennia daylight was the only light source used by terrestrial species for circadian entrainment. In a modern, 24-hour society in which people spend most of their time indoors, it can be assumed that electric lighting, operated both day and night, blurs the distinction between the two, thus compromising circadian entrainment. Without access to daylight, or electric lighting providing comparable amount, spectrum, distribution, duration, and timing, human health and wellbeing may be compromised. This may be particularly true for those confined indoors, such as patients in hospitals and residents in eldercare facilities. Studies to date have examined the effects of daylight on patients[18, 19] and their outcomes,[20, 21] but have not specifically investigated the effects of daylight on the circadian system of those confined indoors.

There are several metrics related to the measurement of daylight through windows. *Daylight factor* is the simplest and most common metric used to quantify daylight in a space. It expresses the potential illuminance inside a room for the worst possible scenario: overcast sky conditions when there is less exterior daylight.[22] Many of the studies of daylight through windows are based on this metric.[23, 24] In addition, there are currently new dynamic metrics based on weather data, which require complex calculations through lighting simulation programs.[25] Several studies of daylighting have been developed using the dynamic metrics of *daylight autonomy* or useful daylight illuminance.[4] These new metrics complement the daylight factor values, to describe the daylight inside a room.[26]

Neither *daylight factor* nor *daylight autonomy* fully describe the impact of daylight on health and wellbeing, because these metrics quantify light only for the visual system. However, Rea and colleagues have proposed a mathematical model of human circadian phototransduction,[15, 27] based on current knowledge of the neuroanatomy and neurophysiology of the human retina, that can be used to quantify one of the many non-visual human responses to light. The model utilizes the empirical, light-induced nocturnal suppression data from published data to characterize the spectral and absolute sensitivities of the human circadian system to light (circadian light; CL_A) while still taking into account the neurophysiology and neuroanatomy of the human retina.[13-15, 28, 29] From CL_A values, it is then possible to determine the magnitude of circadian stimulus (CS). CS is a transformation of CL_A into relative units from 0, the threshold for circadian system activation, to 0.7, response saturation, and is directly proportional to nocturnal melatonin suppression after one-hour exposure (0% to 70%) assuming a fixed, 2.3 mm diameter pupil. Figure 1 illustrates the spectral and absolute sensitivities of the phototransduction model.

Because CS represents the input-output characteristics of the human circadian system from threshold to saturation, it can potentially be a useful metric to quantify how much daylight from windows is available to those confined indoors.[30-32] Based on model predictions, the threshold for activation of the circadian system corresponds to a CS value of 0.1 (see Figure 1). The half saturation constant of acute melatonin suppression, which represents the amount of light needed to achieve 50% of the total suppression amount (i.e., 70%), corresponds to a CS value of 0.35. While there have been no studies linking 35% melatonin suppression to better circadian entrainment, for the purpose of this manuscript, it is hypothesized that exposure to a CS value of 0.35 for at least one hour in the morning would be sufficient to promote daily entrainment.

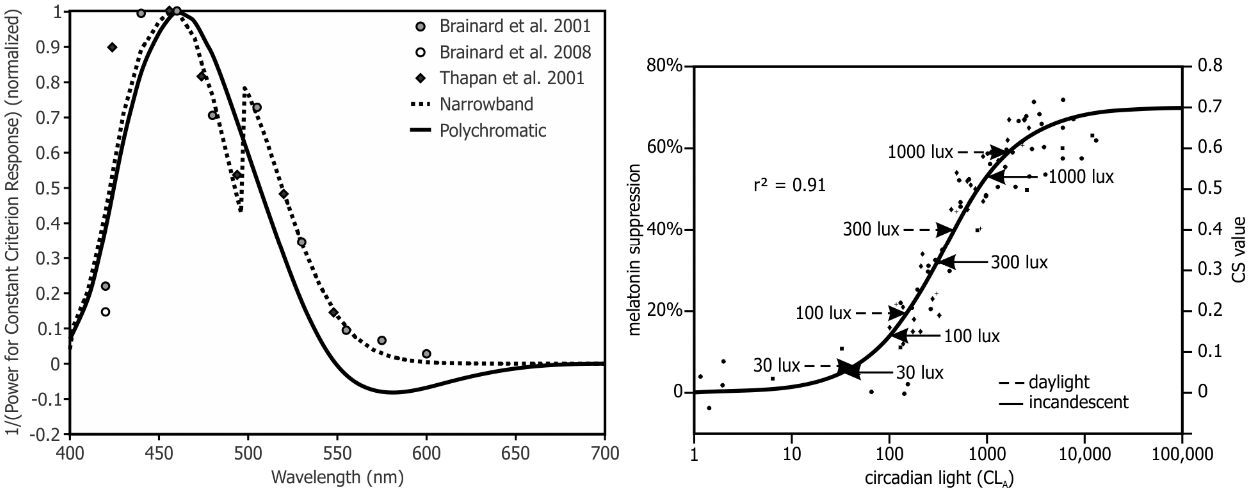


Figure 1. Left: The spectral sensitivity of the human circadian system for narrowband and for polychromatic lights.[15, 27] Right: The relationship between the spectrally weighted levels of circadian light (CL_A) and the measured levels of nocturnal melatonin suppression for different amounts of narrowband light stimuli used in various published studies. [13, 14, 29, 31, 33] Figure from Rea et al., 2014.[34]

The present paper details results of simulations used to determine percentage of days that individuals lying in bed or sitting upright would receive a CS value equal to or greater than 0.35 for at least one hour in the morning, as a function of different window-to-façade ratios, surface reflectances, and latitudes. The goal was to illustrate how the CS metric could be utilized to assist with the selection of window characteristics that are likely to promote circadian entrainment and thus benefit health and wellbeing in those confined indoors.

2. Methods

2.1. Selecting the room model

2.1.1. Characteristics of the room model

A virtual room measuring 3.0 meters (m) wide × 6.0 m deep × 3.0 m high, the size of a typical hospital room in the studied locations, was used to analyze various daylighting strategies. The room ceiling, walls and floor had a thickness of 0.25 m. Square windows of variable sizes were centered in the 3.0 m wide façade. The double pane window was 0.05 m thick with a visible transmission of 0.75. Daylight simulations were conducted using the window sizes listed in Table 1 with two room surface average reflectances, also listed in Table 1. The inner surfaces of the room were assumed to display Lambertian reflectances. The luminous intensity of reflected light was therefore directly proportional to the cosine of the angle between the observer's line of sight and the surface normal. This study sample did not cover all possible room configurations, but aimed to show a typical room as a case study. Therefore, a total of 12 calculation models were established, as described in Table 1.

Table 1. Calculation models (B = bright/high-reflectance surfaces; D = dark/low-reflectance surfaces)

Model	Window/ façade	Window surface (m²)	Window dimensions (m)	Glass surface (m²)	Glass factor	Walls reflectance	Floor reflectance	Ceiling reflectance
10.B	10%	0.90	0.95·0.95	0.64	0.75	0.8	0.6	0.8
10.D	10%	0.90	0.95·0.95	0.64	0.75	0.4	0.2	0.6
20.B	20%	1.80	1.34·1.34	1.41	0.75	0.8	0.6	0.8
20.D	20%	1.80	1.34·1.34	1.41	0.75	0.4	0.2	0.6
30.B	30%	2.70	1.64·1.64	2.22	0.75	0.8	0.6	0.8
30.D	30%	2.70	1.64·1.64	2.22	0.75	0.4	0.2	0.6
40.B	40%	3.60	1.90·1.90	3.06	0.75	0.8	0.6	0.8
40.D	40%	3.60	1.90·1.90	3.06	0.75	0.4	0.2	0.6
60.B	60%	5.40	2.32·2.32	4.71	0.75	0.8	0.6	0.8
60.D	60%	5.40	2.32·2.32	4.71	0.75	0.4	0.2	0.6
80.B	80%	7.20	2.68·2.68	6.40	0.75	0.8	0.6	0.8
80.D	80%	7.20	2.68·2.68	6.40	0.75	0.4	0.2	0.6

2.1.2. Study on the horizontal plane

In order to estimate CS received at the eye level of a patient lying in bed, CS was calculated at points on a horizontal plane 0.60 m above the floor, a typical height for a hospital bed. To account for different bed locations in the room, the calculation points were spaced at 0.30 m intervals from the window/façade, 0.50 m from the side walls, and 1.00 m from the center row, defining one center axis and two side axes. Figure 2 shows the location of these study points, as well as all variables of the calculation model.

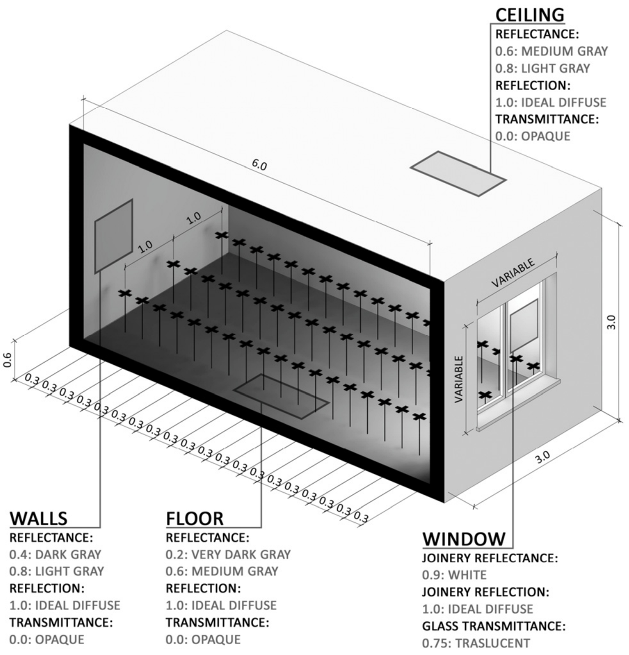


Figure 2. Room model for a patient lying in bed.

2.1.3. Study on the vertical plane

In order to estimate CS received at the eye level of a patient sitting upright and facing forward, CS was calculated at points on a vertical plane. The points were located at a height of 1.00 m above the floor, according to the typical height of a chair, 0.50 m from the side wall, and spaced 0.30 m apart as shown in Figure 3.

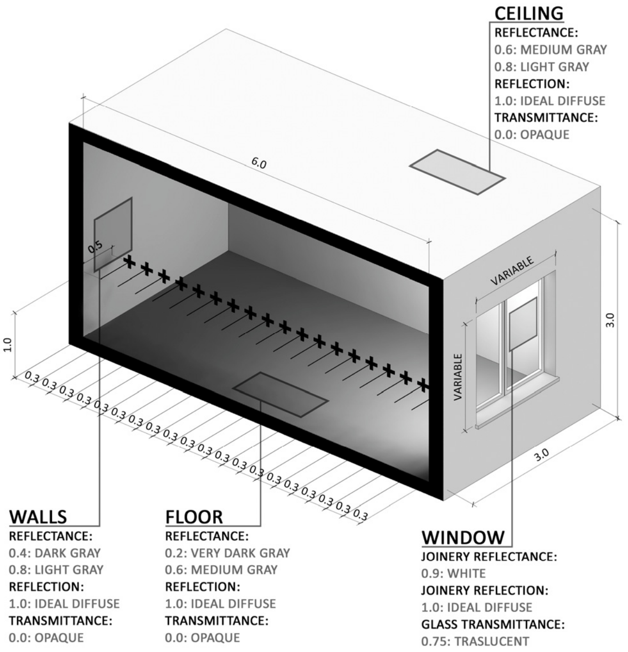


Figure 3. Room model for a patient sitting upright.

2.2. Selecting the calculation metrics

2.2.1. Calculation of average illuminance

The average illuminance value was calculated at the study points shown in Figures 2 and 3 using the lighting simulation program DAYSIM 3.1.[35] These illuminance values were then used to determine CS at the study points.

2.2.2. Calculation of average CS

In order to determine the CS values, Rea et al.'s model of human circadian phototransduction was used to estimate CL_A from the source spectral power distribution (SPD) and the illuminance levels obtained at each study point.[15, 27, 28] The spectrum of daylight was defined by the CIE Standard Illuminant D65,[36, 37] roughly corresponding to a midday sun in Western and Northern Europe. CS magnitudes were determined from the calculated CL_A values using the following formula:

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

CS is directly proportional to the predicted levels of light-induced nocturnal melatonin suppression from threshold to saturation, assuming a pupil size of 2.3 mm and an exposure duration of one hour.

2.2.3. Calculation of CS autonomy

For the present study, *CS autonomy* was defined as the percentage of days in the year when CS is equal to or greater than 0.35 for at least one hour in the morning.[38, 39] It was hypothesized that achieving this half-maximum saturation would be sufficient to promote circadian entrainment. As shown in Figure 1, the half-saturation constant of acute melatonin suppression, which represents the amount of light needed to achieve 50% of the total suppression amount (i.e., 70%), corresponds to a CS value of 0.35. In a controlled laboratory condition, Zeitzer et al.[40] showed that, in response to three consecutive days of a five-hour light exposure (4100 K light source), the human circadian system achieves a half-maximum phase shifting response at light levels ranging from 50 to 160 lux at the eye, which is equivalent to a CS value of 0.04 to 0.15. Given that these results were obtained under controlled laboratory conditions and that the light pulse was given for five hours, we hypothesized that a CS of 0.35 for at least one hour in the morning should be sufficient to promote circadian entrainment.

Using a CS calculator based upon the model of phototransduction[15, 27] it was determined that the average illuminance of CIE Standard Illuminant D65 needed to meet a CS of 0.35 corresponds to 233 photopic lux at the eye. CS autonomy was thus determined by calculating daylight autonomy for this photopic illuminance value between 8:00 AM and 12:00 PM. Since the human circadian system has, on average, a period slightly greater than 24 hours, morning light is needed to advance the biological clock and promote circadian entrainment to local time on Earth; therefore, the CS autonomy metric focuses on providing the patient with morning light. It is important to keep in mind that, if possible, all-day high circadian stimulation would be preferred, but given other constraints, we are proposing that, at a minimum, a CS of 0.35 should be provided during the morning hours. The analysis of the results determines the percentage of days throughout the year that the CS value is equal to or greater than 0.35 for at least one hour in the morning.

2.2.4. Calculation of maximum daylight autonomy

In order to have an illuminance-based glare analysis, *maximum daylight autonomy* was defined, for the present study, as the percentage of the year when the illuminance reached a high value due to the incidence of sunlight, effectively a "glare zone" where sunlight falls inside the room. The maximum daylight autonomy was calculated for five-minute intervals throughout the year. The glare from direct sun may be too high for patient comfort, although it can be beneficial for their health and wellbeing.[41] The maximum daylight autonomy was calculated by DAYSIM 3.1 using the daylight autonomy calculation with a threshold of 5000 lux.

2.3. Selecting the calculation conditions

2.3.1. Location of the room

Two locations in Europe at different latitudes and with different sky conditions were chosen to illustrate the impact of variation of daylight availability: (1) London, UK, at 50° north latitude and with predominantly overcast skies; and (2) Madrid, Spain, at 40° north latitude and with predominantly clear skies. Weather data for both locations are defined by the EnergyPlus reference.[42]

2.3.2. Orientation of the window

The window orientation was north for all calculation models and both locations. Illuminance values are lower for north-facing windows,[4] therefore representing the worst case scenario for daylight illuminance and CS.

2.4. Selecting the calculation program

DAYSIM 3.1 is a validated RADIANCE-based daylighting analysis tool that uses a daylight coefficient approach combined with the Perez all-weather sky model[43] to predict the amount of daylight in and around buildings, based on direct normal and diffuse horizontal irradiances taken from a climate file. DAYSIM was developed to provide a more efficient calculation of illuminance or luminance time series under varying sky conditions than that provided by RADIANCE in its original form. This lighting software has been validated by several researchers.[35, 44] The calculation parameters used by this program in this research are shown in Table 2.

Table 2. Parameters of the calculation program

Ambient Bounces	7
Ambient Divisions	1500
Ambient Super-Samples	100
Ambient Resolution	300
Ambient Accuracy	0.05
Limit Reflection	10
Specular Threshold	0.0000

Specular Jitter	1.0000
Limit Weight	0.0040
Direct Jitter	0.0000
Direct Sampling	0.2000
Direct Relays	2
Direct Pretest Density	512

3. Results

3.1. Average CS

Following the methodology described above, Figure 4 shows the average CS values at the study points representing the eyes of a patient located in London, lying face up on a bed in a room with high reflectances and a north-facing façade. CS values are shown for different window sizes ranging from 10 to 80% of the façade area. The maximum daylight autonomy (i.e., areas likely to have direct sun) is also indicated, measured at the study points on the central axis. Figure 4 also shows the average CS values at the study points located on the vertical plane, representing the position of a patient sitting upright and facing forward.

As expected, the CS values are higher in the zone near the façade, gradually decreasing toward the back of the room. Obviously, the larger windows provide higher CS. However, as can be deduced from the results, the window area and resulting CS values are not directly proportional. Rooms with window-to-façade ratios of 60 and 80% provide similar CS values; therefore, there is no significant benefit to having a particularly large window. The CS values observed on the side axes are similar to those measured on the central axis, except in the rooms with small windows (window-to-façade ratios of 10-30%). That is to say, windows with an area higher than 40% of the façade allow an evenly distributed CS.

Significantly, daylight provided greater CS on the vertical plane compared to the horizontal plane, suggesting an advantage for patients to be sitting rather than lying down for a period in the morning. For the room with high reflectance walls in London, a window with an area equal to 20% of the façade provides a CS value higher than 0.35 only within the first 3.0 m from the façade for a patient lying in bed. However, for a sitting patient, this distance increases to over 5.0 m. To provide the CS criterion in the entire room, a window-to-façade ratio of at least 40% is needed for a patient lying down and 30% for the patient sitting up.

For the room with low reflectance surfaces in London, a typically overcast location, even a window with an area equal to 80% of the façade is not large enough to provide a CS value of 0.35 in the entire room for a lying patient; however, a window-to-façade ratio of 40% or higher meets the criterion CS for a sitting patient, even in this low reflectance room.

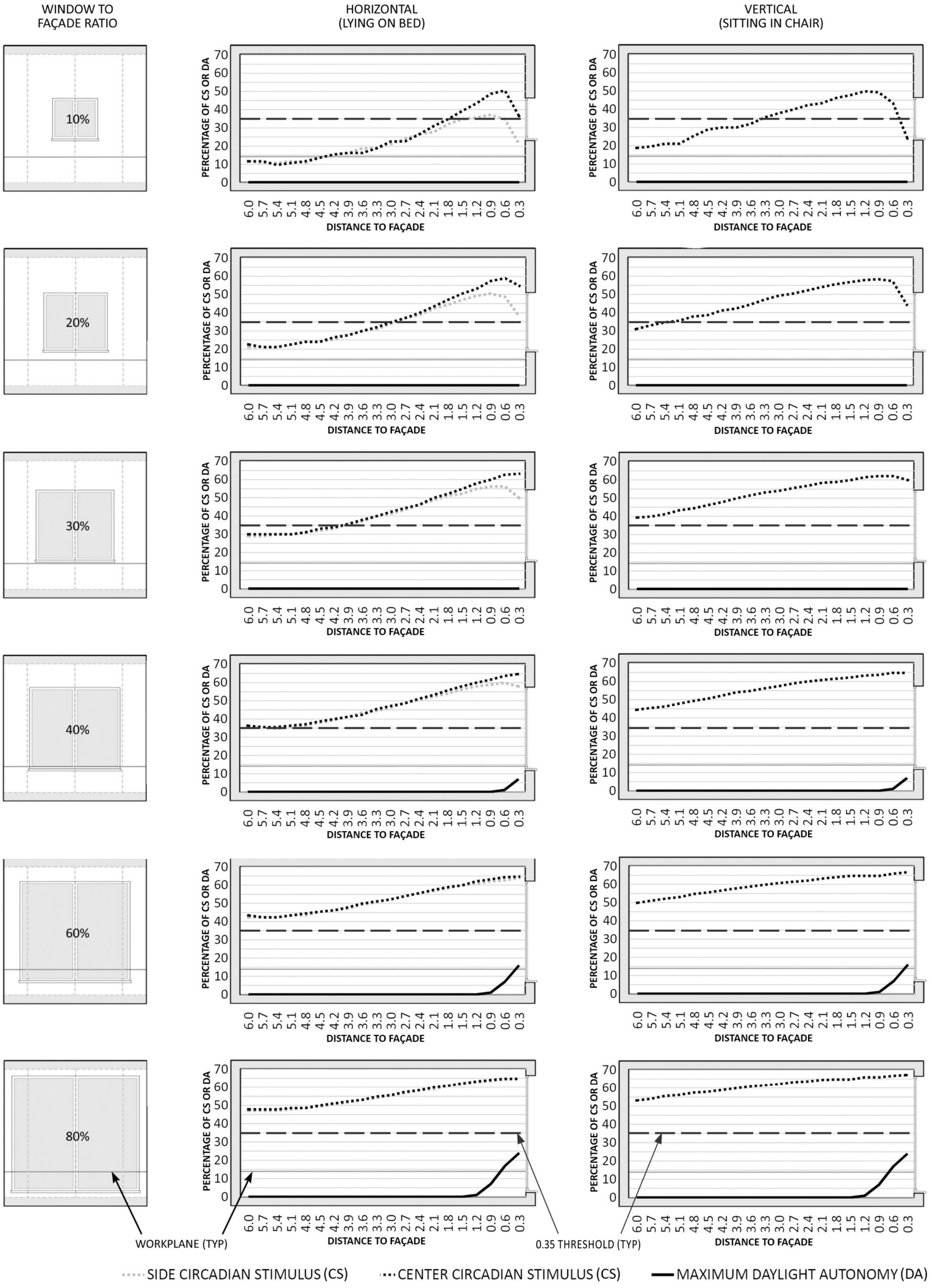
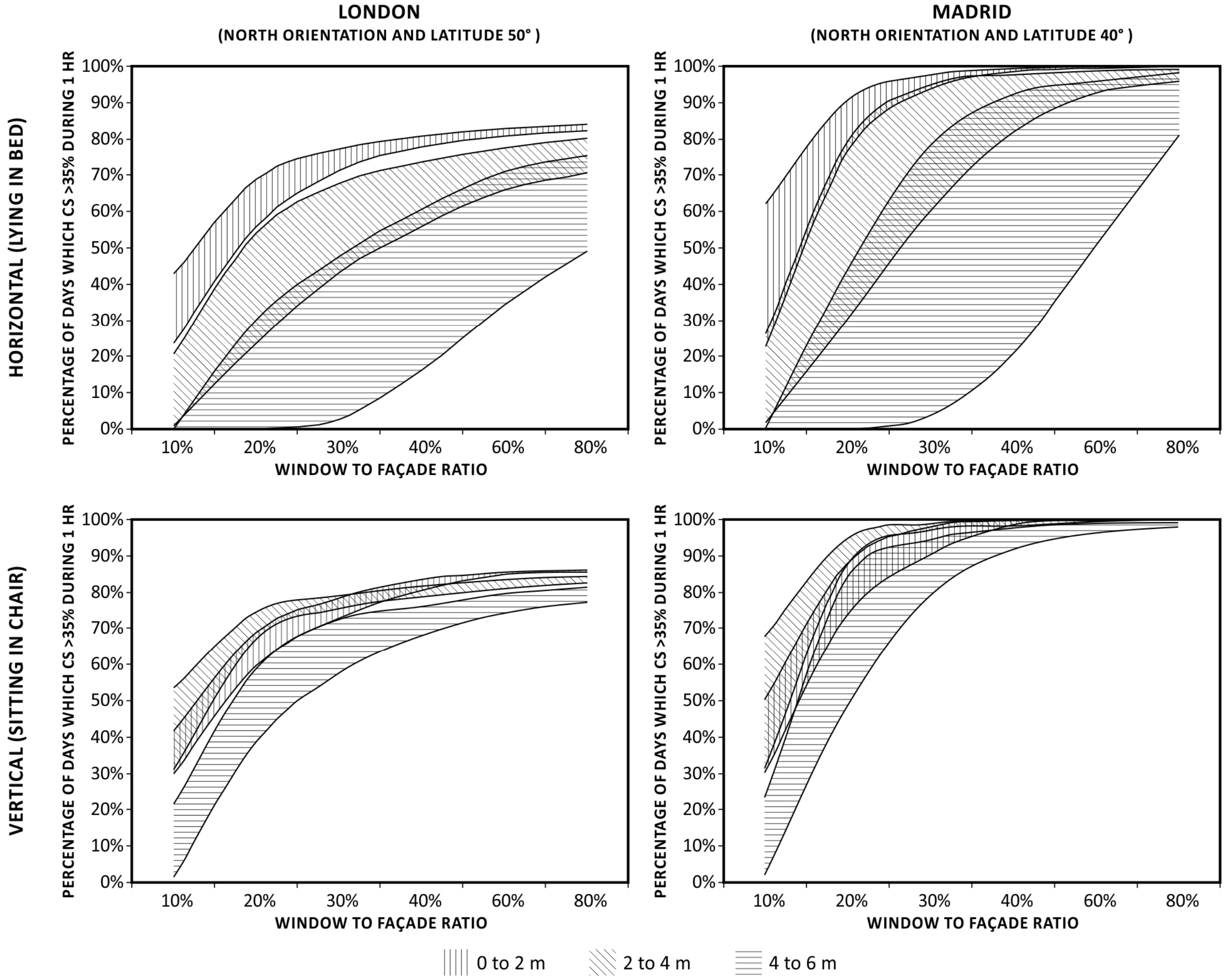


Figure 4. Average circadian stimulus (CS) values calculated between 8:00 AM and 12:00 PM on horizontal and vertical planes for a high reflectance room in London. The maximum daylight autonomy (DA) is also indicated, measured at the study points on the central axis.

For Madrid, a location with typically clear skies, a window with an area equal to 10% of the façade is sufficient to obtain a CS value greater than 0.35 at a distance of 2.0 m from the façade. This ratio should be increased to 20% if the surfaces of the room have low reflectance. A room with high reflectance surfaces and a window-to-façade ratio higher than 30% provides a good CS on the entire horizontal plane. In the case of low reflectance surfaces, the window size must reach 80% of the façade area to provide an average CS value higher than 0.35 in the entire room.

3.2. CS autonomy

Figure 5 shows CS autonomy in London and in Madrid in three zones within the room: near the façade from 0 to 2 m, between 2 to 4 m, and the back of the room from 4 to 6 m from the façade.



LONDON
(NORTH ORIENTATION AND LATITUDE 50°)

MADRID
(NORTH ORIENTATION AND LATITUDE 40°)

Figure 5. CS autonomy as a function of window-to-façade ratio in London and Madrid. The upper and lower boundary of each zone represents high (70%) and low (35%) mean surface reflectance values, respectively. The vertical-hatch represents CS autonomy in the zone near the façade, from 0 to 2 m; the diagonal-hatch is the zone from 2 to 4 m; and the horizontal-hatch is the zone in the back of the room, from 4 to 6 m from the façade.

As can be seen in Figure 5, the window-to-façade ratio and surface reflectance values can be used to determine the percentage of days that a target CS value is reached. Thus, for a patient lying in bed at a hospital in London, a window-to-façade ratio of 30% and a mean room surface reflectance, close to 0.55, provides a criterion CS value in the zone close to the façade during 75% of the year. For the middle of the room and a mean room surface reflectance, the window-to-façade ratio must be larger, at least 60%, to meet this CS criterion during 75% of the year. The range between 4 and 6 m is wider than the others, demonstrating that the importance of selecting appropriate surface reflectances to achieve the desired CS value increases as the room deepens.

Figure 5 also shows the CS autonomy for a patient lying in bed at a hospital in Madrid. In this case, a window-to-façade ratio equal to or higher than 40% and a mean surface reflectance provides a criterion CS value in the zone close to the façade during the entire year. The percentage of days in which the CS values reach the proposed criterion is noticeably higher in Madrid compared to London. Moreover, a window-to-façade ratio of 40% is enough to meet the proposed CS criterion during 90% of the year in the middle zone of the room. As with the calculations for London, the importance of selecting the appropriate surface reflectances to achieve the desired CS value increases as the room deepens.

In London, the zone from 2 to 4 m allows the best position for a sitting patient, except in the case of larger windows, as shown in Figure 5. The smaller windows, with a window-to-façade ratio between 10 and 30%, produce shadows in the zone of the walls near the façade. Therefore, a window-to-façade ratio equal to 30% with a mean surface reflectance provides the desired CS criterion in the zone from 0 to 4 m during approximately 75% of the year. For the back of the room, the window-to-façade ratio must be larger, at least 60% to meet this CS criterion for 75% of the year.

For sitting patients, the percentage of days that the CS reaches the criterion value is noticeably higher in Madrid compared to London. For a window-to-façade ratio equal to or higher than 40% and a mean value of reflectance, the CS reaches the desired criterion in the zones between 0 and 4 m during the entire year. Moreover, a window-to-façade ratio equal to 40% is enough to reach the desired CS value during 90% of the year in the back of the room.

3.3. Maximum daylight autonomy

According to the metrics described above, maximum daylight autonomy could serve as an indicator of the percentage of the year that direct sunlight falls inside the room. Daylight can produce a potential benefit for patients, except when direct solar radiation is causing thermal or visual discomfort. As described in Figure 4, the largest windows allow sunlight in the zone near the façade. Specifically, window-to-façade ratios higher than 60% allow sunlight in the first meter from the façade. It is important to note that the area receiving maximum daylight autonomy would be much larger on façades other than the north façade modeled in this paper.

4. Conclusion

The goal of the present research was to illustrate how the CS metric could be utilized to assist with the selection of window characteristics that are likely to deliver daylight in a patient's room to promote circadian entrainment and thus potentially benefit health and wellbeing in those confined indoors. A more extensive study of CS autonomy can be developed using Figure 5, serving as a tool that could assist architects, engineers, and designers to determine optimal window size according to a target percentage of days throughout the year during which the CS value is 0.35 or higher. It is important to keep in mind, however, that it is still not known whether humans adapt to lower levels of light for the circadian system and whether the CS value of 0.35 may be enough to maintain entrainment. The selected CS criterion assumes a duration exposure of one hour; whether longer duration exposures will require lower CS values for entrainment also requires further investigation. Regardless, the metric proposed here is a step towards considering the non-visual effects of light in daylighting design. This metric can be used as a guideline to assist architects, engineers and designers to provide healthy indoor lighting that impacts more than just vision.

Funding

This study was funded by the Lighting Research Center at Rensselaer Polytechnic Institute and by the University of Seville, Instituto Universitario de Arquitectura y Ciencias de la Construcción.

Acknowledgements

The authors would like to acknowledge Rebekah Mullaney and Sarah Hulse for editing the manuscript and Dennis Guyon for preparing several of the graphics.

References

1. Treado S, Gillette G and Kusuda T. Daylighting with Windows, Skylights, and Clerestories. *Energy and Buildings*. 1984; 6: 319-30.
2. Li DHW. A review of daylight illuminance determinations and energy implications. *Applied Energy*. 2010; 87: 2109-18.
3. Acosta I, Munoz C, Campano MA, et al. Analysis of daylight factors and energy saving allowed by windows under overcast sky conditions. *Renewable Energy*. 2015; 77: 194-207.
4. Munoz C, Esquivias PM, Moreno D, et al. Climate-based daylighting analysis for the effects of location, orientation and obstruction. *Light Res Technol*. 2014; 46: 268-80.
5. Alzoubi HH and Al-Zoubi AH. Assessment of building façade performance in terms of daylighting and the associated energy consumption in architectural spaces: Vertical and horizontal shading devices for southern exposure facades. *Energy Conversion and Management*. 2010; 51: 1592-9.
6. Villalba A, Pattini A and Correa E. An approach to urban tree daylight permeability simulation using models based on louvers. *Building and Environment*. 2014; 73: 75-87.
7. Sanati L and Utzinger M. The effect of window shading design on occupant use of blinds and electric lighting. *Building and Environment*. 2013; 64: 67-76.
8. Boyce PR. The Impact of Light in Buildings on Human Health. *Indoor and Built Environment*. 2010; 19: 8-20.
9. Figueiro M and Rea M. Office lighting and personal light exposures in two seasons: Impact on sleep and mood. *Light Res Technol*. 2014: 1477153514564098.
10. Van Cauter E, Spiegel K, Tasali E, et al. Metabolic consequences of sleep and sleep loss. *Sleep Med*. 2008; 9 Suppl 1: S23-8.
11. Leproult R, Holmback U and Van Cauter E. Circadian misalignment augments markers of insulin resistance and inflammation, independently of sleep loss. *Diabetes*. 2014; 63: 1860-9.
12. Stevens RG. Light-at-night, circadian disruption and breast cancer: assessment of existing evidence. *Int J Epidemiol*. 2009; 38: 963-70.
13. Brainard GC, Hanifin JP, Greeson JM, et al. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. *J Neurosci*. 2001; 21: 6405-12.

14. Thapan K, Arendt J and Skene DJ. An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans. *The Journal of Physiology*. 2001; 535: 261-7.
15. Rea MS, Figueiro MG, Bullough JD, et al. A model of phototransduction by the human circadian system. *Brain Res Rev*. 2005; 50: 213-28.
16. Khalsa SB, Jewett ME, Cajochen C, et al. A phase response curve to single bright light pulses in human subjects. *J Physiol*. 2003; 549: 945-52.
17. Figueiro MG, Nonaka S and Rea MS. Daylight exposure has a positive carry-over effect on nighttime performance and subjective sleepiness. *Light Res Technol*. 2013.
18. Kriszbacher I, Bodis J, Boncz I, et al. The time of sunrise and the number of hours with daylight may influence the diurnal rhythm of acute heart attack mortality. *Int J Cardiol*. 2010; 140: 118-20.
19. Bullough JD, Rea MS and Figueiro MG. Of mice and women: light as a circadian stimulus in breast cancer research. *Cancer Causes Control*. 2006; 17: 375-83.
20. Alzoubi HH and Al-Rqaibat SM. The Effect of Hospital Design on Indoor Daylight Quality in Children Section in King Abdullah University Hospital, Jordan. *Sustainable Cities and Society*. 2015; 14: 449-55.
21. Choi JH, Beltran LO and Kim HS. Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility. *Building and Environment*. 2012; 50: 65-75.
22. Commission Internationale de l'Éclairage. *CIE S 017/E:2011 International Lighting Vocabulary* Vienna: Commission Internationale de l'Éclairage, 2011.
23. CIBSE. *Daylighting and window design*. London: Chartered Institution of Building Services Engineers, 1999.
24. Love JA. Determination of the Daylight Factor under Real Overcast Skies. *JIES*. 1993; 22: 176-82.
25. Reinhart CF, Mardaljevic J and Rogers Z. Dynamic daylight performance metrics for sustainable building design. *Leukos*. 2006; 3: 1-25.
26. Boyce PR and Smet KAG. LRT symposium 'Better metrics for better lighting' – a summary. *Light Res Technol*. 2014; 46: 619-36.
27. Rea MS, Figueiro MG, Bierman A, et al. Modelling the spectral sensitivity of the human circadian system. *Light Res Technol*. 2012; 44: 386-96.
28. Rea MS, Figueiro MG, Bierman A, et al. Circadian light. *J Circadian Rhythms*. 2010; 8: 2.
29. Brainard GC, Sliney D, Hanifin JP, et al. Sensitivity of the human circadian system to short-wavelength (420-nm) light. *J Biol Rhythms*. 2008; 23: 379-.
30. Leslie RP, Radetsky LC and Smith AM. Conceptual design metrics for daylighting. *Light Res Technol*. 2012; 44: 277-90.
31. Figueiro MG, Brons JA, Plitnick B, et al. Measuring circadian light and its impact on adolescents. *Light Res Technol*. 2011; 43: 201-15.
32. Barroso A, Simons K and de Jager P. Metrics of circadian lighting for clinical investigations. *Light Res Technol*. 2014; 46: 637-49.
33. West KE, Jablonski MR, Warfield B, et al. Blue light from light-emitting diodes elicits a dose-dependent suppression of melatonin in humans. *Journal of applied physiology (Bethesda, Md : 1985)*. 2011; 110: 619-26.
34. Rea MS and Figueiro MG. Quantifying light-dependent circadian disruption in humans and animal models. *Chronobiol Int*. 2014; 31: 1239-46.
35. Reinhart CF and Breton PF. Experimental Validation of Autodesk® 3ds Max® Design 2009 and Daysim 3.0. *LEUKOS*. 2009; 6: 7-35.
36. Commission Internationale de l'Éclairage. *CIE 15.2-1986 Colorimetry*. Vienna: Commission Internationale de l'Éclairage, 1986.
37. Commission Internationale de l'Éclairage. *CIE 051.2-1999 A Method for Assessing the Quality of Daylight Simulators for Colorimetry*. Vienna: Commission Internationale de l'Éclairage, 1999.
38. Smith KA, Schoen MW and Czeisler CA. Adaptation of human pineal melatonin suppression by recent photic history. *J Clin Endocrinol Metab*. 2004; 89: 3610-4.
39. Hebert M, Martin SK, Lee C, et al. The effects of prior light history on the suppression of melatonin by light in humans. *J Pineal Res*. 2002; 33: 198-203.
40. Zeitzer JM, Khalsa SB, Boivin DB, et al. Temporal dynamics of late-night photic stimulation of the human circadian timing system. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology*. 2005; 289: R839-R44.
41. Leung AY, Cheung MK and Chi I. Supplementing vitamin D through sunlight: associating health literacy with sunlight exposure behavior. *Arch Gerontol Geriatr*. 2015; 60: 134-41.

42. Lawrence Berkeley National Laboratory. The Refererence to EnergyPlus Calculations. *EnergyPlus Engineering Reference*. Lawrence Berkeley National Laboratory, 2012.
43. Perez R, Seals R and Michalsky J. All-Weather Model for Sky Luminance Distribution - Preliminary Configuration and Validation. *Solar Energy*. 1993; 50: 235-45.
44. Reinhart CF and Walkenhorst O. Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds. *Energy and Buildings*. 2001; 33: 683-97.