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Analysis of Circadian Stimulus Provide by Daylighting in Educational Uses

Ignacio Acosta [1+], Juan Francisco Molina [2] and Miguel Ángel Campano [1]

[1] Instituto Universitario de Arquitectura y Ciencias de la Construcción. Universidad de Sevilla.

[2] Departamento de Expresión Gráfica Arquitectónica. Universidad de Sevilla.

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. Daylighting is an ideal light source for circadian entrainment, especially for educational use. Architectural and design features, including window size and room reflectances, impact circadian stimulus levels. DAYSIM simulations were used to determine the average circadian stimulation that students in classrooms would receive as a function of different window-to-façade ratios, window position and room reflectances. The present paper provides a tool to assist designers with choice of fenestration and interior design to promote circadian entrainment.

Keywords: circadian stimulus, daylighting, energy efficiency, educational use.

1. Introduction

Window design is the key element for allowing daylight inside buildings of educational use [1]. The proper design of windows can also 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, as well as the relationship of these shading devices with electric lighting [7]. As reviewed in Boyce (2010) [8], recent studies have investigated whether there is a relationship between light/daylight and health outcomes. 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 system. Light is the major synchronizer of circadian rhythms to the Earth's 24-hour (h) light-dark cycle. Circadian rhythms in our bodies, such as the sleep-wake cycle, repeat approximately every 24 h. In the absence of any external cue, human circadian rhythms run with an average period slightly greater than 24 h (approximately 24.2 h). Morning light resets the biological clock daily and promotes entrainment to the natural 24-h light-dark pattern.

There are several metrics related to the measurement of daylight through windows. Daylight factor is the most common measure to quantify daylight in a space [9]. However, there are currently new dynamic metrics based on weather data, which require complex calculations through lighting simulation programs [10]. Neither the daylight factor nor dynamic metrics fully describe the quality of daylight on health and wellbeing, because all of these metrics represent the quantification of light only for the visual system.

Daylight is potentially the ideal light source for synchronizing the human circadian system to local time. It provides the right amount, spectrum, distribution, duration, and timing needed for circadian entrainment. In a modern, 24-h society populated by people who spend most of their time indoors, it is quite reasonable to suppose that electric lighting, operated during the day and the night, blurs the distinction between day and night, compromising our entrainment to local time. In other words, without access to daylight or electric lighting providing comparable amount, spectrum, distribution, duration, and timing, human health and

[+]Corresponding author. Tel.: + 0034 647 550 654; fax: + 0034 954 457 234.
E-mail address: iacosta@us.es.

wellbeing may be compromised. This may be particularly true for students who must be mindful in classroom.

2. Methodology

2.1. Choosing the room model

A virtual room 8.0 meters (m) wide by 8.0 m deep by 3.0 m high, the size of a typical classroom, was used to analyze various daylighting strategies. The room ceiling, walls and floor had a thickness of 0.25 m. Horizontal windows of variable sizes were placed in the North façade. The double pane window was 0.05 m thick with a visible transmission of 0.75. Daylight simulations were conducted using window sizes listed in Table 1 with two room surface average reflectances, representing bright or dark surface rooms, also listed in Table 1. The inner surfaces of the room are assumed to be diffuse and the Lambertian reflection of daylight is therefore directly proportional to the cosine of the angle between the observer's line of sight and the surface normal.

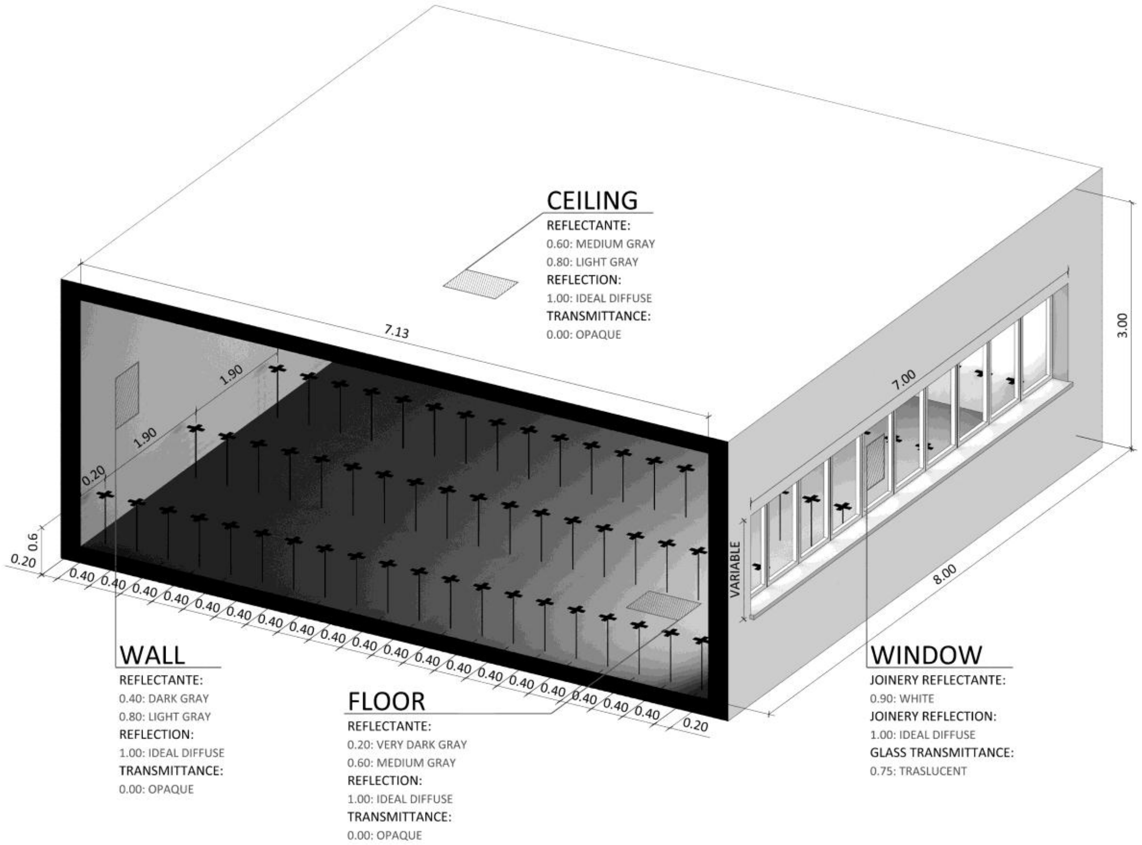

Fig. 1: Virtual room model for a classroom of educational use.

Obviously, this study sample does not cover all possible room configurations, but aims to show a typical room as a case study. Therefore, a total of 12 calculation models are established, as described in Table 1.

In order to estimate the circadian stimulus (CS) received at the eyes of a student, calculations were set on a horizontal plane 0.60 m above the floor, a typical height for a classroom table. To account for different table locations in the classroom, the calculation points were spaced at 0.40 m intervals from the window wall, 0.20 m from the side walls, and 1.00 m from the center row, defining one center axis and several side axes. Fig. 1 shows the location of these study points, as well as all variables of the calculation model.

2.2. Choosing the calculation metrics

The average illuminance value was calculated at the study points shown in Fig. 1 using the lighting simulation program DAYSIM 3.1 [11]. These illuminance values were then used to determine the CS at the study points.

Table 1: Calculation models (B=high reflectance surfaces; D=low reflectance surfaces).

Model	Window/ façade	Window position	Glass factor	Walls reflectance	Floor reflectance	Ceiling reflectance
30.C.B	30%	Centered	0.75	0.8	0.6	0.8
30.C.D	30%	Centered	0.75	0.4	0.2	0.6
30.U.B	30%	Upper	0.75	0.8	0.6	0.8
30.U.D	30%	Upper	0.75	0.4	0.2	0.6
40.C.B	40%	Centered	0.75	0.8	0.6	0.8
40.C.D	40%	Centered	0.75	0.4	0.2	0.6
40.U.B	40%	Upper	0.75	0.8	0.6	0.8
40.U.D	40%	Upper	0.75	0.4	0.2	0.6

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 [12] 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 [11]-[13]. 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

In order to determine the CS values, Rea et al.'s model of phototransduction by the human circadian system was used to estimate CL_A from the source spectral power distribution (SPD) and the illuminance levels obtained at each study point [14]-[16]. The spectrum of daylight was defined by the CIE Standard Illuminant D65 [17], [18] 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:

$$CS= 0.7 \cdot (1- 1/(1+ (CL_A/355.7)^{1.1026}))$$

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 the duration of exposure of 1 h.

2.3. Choosing the calculation conditions

The location of the room model is London, UK, at 50 º north latitude and with predominantly overcast skies. Weather data for that location is defined by the EnergyPlus reference [19]. The window orientation is north for all calculation models. Illuminance values are lower for north-facing windows [4], therefore representing the worst case scenario for determining daylight illuminance and CS.

3. Results

3.1. Calculation

Following the methodology described above, Fig. 2 shows the average CS value at the study points representing the eyes of a student. The maximum daylight autonomy (i.e., areas likely to have direct sun) is also indicated, measured at the study points on the central axis.

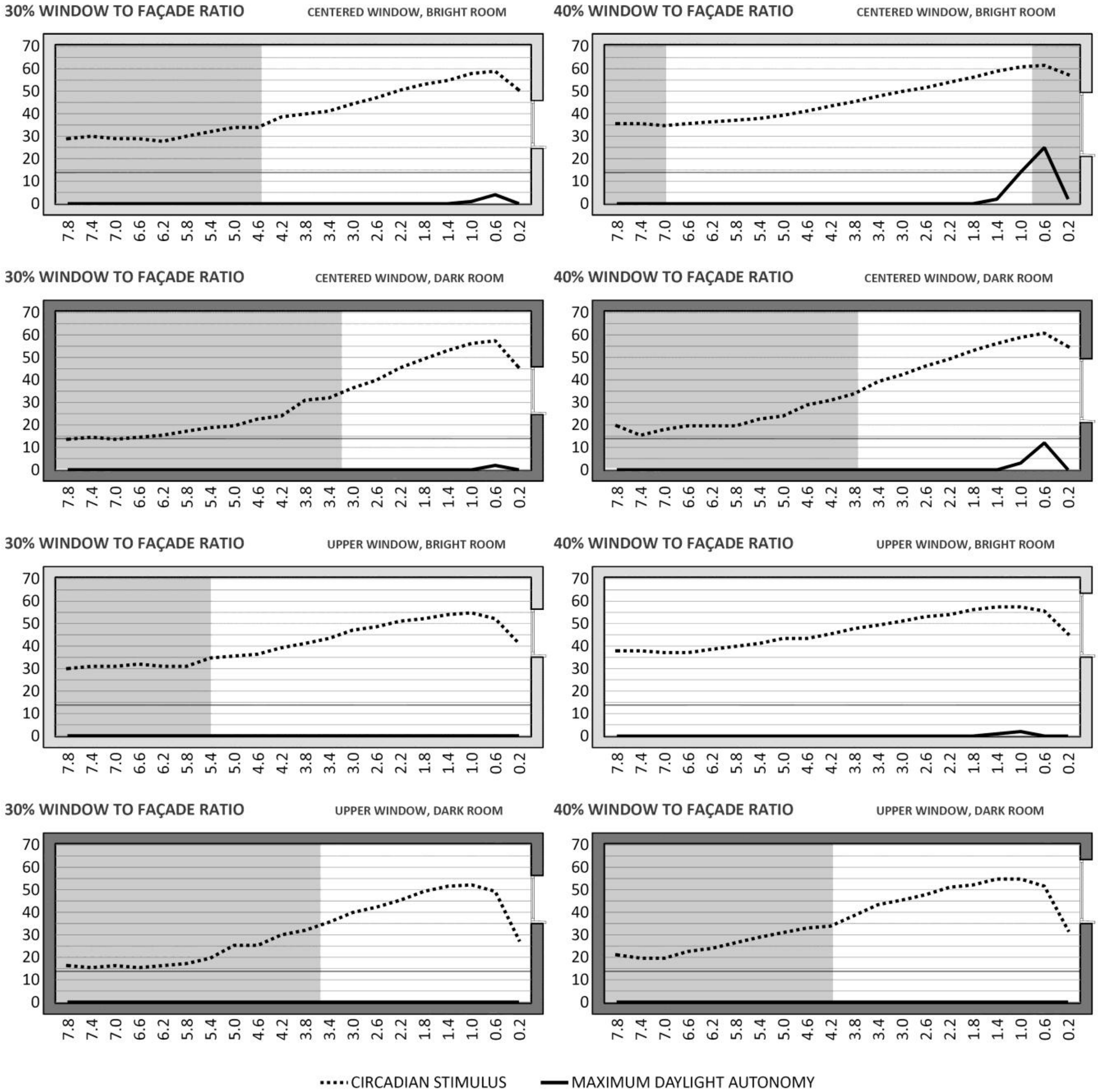

Fig. 2: Average circadian stimulus (CS) and maximum daylight autonomy (DAmax).

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 35%. For the purpose of this research, it is hypothesized that exposure to a CS value of 35% for at least 1 h in the morning would be sufficient to promote daily entrainment. Therefore, the zone that meet an average CS value higher than 35% is highlighted in Fig. 2.

3.2. Analysis of results

As can be observed in Fig. 2, the classroom models which consider a 30% window to façade ratio produce a low CS in the back of the room. This zone decreases in the case of a window in upper position and high reflectance surfaces, although it does not disappear.

In the case of the classroom models with a 40% window to façade ratio, the average CS throughout the year is enough to reach a value of 35%, considering a window in upper position and high reflectance surfaces.

As can be observed in dark room models, the reflectance values of the inner surfaces of the room are decisive to determine the zone where the CS is enough to promote daily entrainment. A dark room produce a low CS value in the half area of the room, regardless of the window size and position. On the other hand, the window position also affects to the average CS value, because the windows in upper position allow a proper CS value in a larger zone.

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