International Journal of Engineering and Technology, Vol. 11, No. 2, April 2019

Analysis of Visual Comfort and Circadian Stimulus Provided by Window Design in Educational Spaces

I. Acosta, M. A. Campano, J. F. Molina, and J. Fernández-Agüera

Abstract—**Light is the main variable which affects to the circadian rhythm, promoting up to 70% of the melatonin suppression. In comparison with the visual system, the circadian system requires more light to be activated and is more sensitive to blue light. As can be deduced, daylighting represents an ideal light source for circadian entrainment. Architectural and design features, such as window size and room reflectance, impact the amount of circadian stimulus that occupants will receive. This study aims to quantify the circadian stimulus promoted in classrooms, according to the window size and reflectance of the surfaces. A first trial is carried out, monitoring the spectral power distribution perceived by the eyes of the students according to different orientations and observer's positions. Secondly, several simulations are developed, using the daylight simulation program DaySim 3.1 and defining a classroom model with a variable window size and reflectance. The results show the noticeable impact of the reflectance of the inner surfaces in the circadian stimulus calculation, as well as the effect of the window size.**

Index Terms—**Circadian stimulus, daylight autonomy, visual comfort, window.**

I. Introduction

Window design is the key element for allowing natural light inside buildings [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 [3], [4] in terms of the light distribution and potential lighting energy savings. 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]. Recent studies have investigated whether there is a relationship between the spectrum of daylight and health outcomes [8]. In addition, light reaching the retina has a profound effect on human health and well-being. Light is the major synchronizer of circadian rhythms to the natural light-dark cycle. Circadian rhythms in our bodies repeat at approximately 24 h. In the absence of any external cue, human circadian rhythms will run with an average period slightly greater than 24 h. Morning light will reset the biological clock daily and promote entrainment to the natural 24 h light-dark pattern.

There are many metrics related to the measurement of daylight through windows. Daylight factor is the simplest and most common measure to quantify the 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 [9]. Many of the studies of daylight through windows are based in this metric [10], [11]. However, there are now new dynamic metrics based on weather data, which require complex calculations through lighting simulation programs [12]. Several studies of daylighting have been developed using the dynamic metrics of daylight autonomy or useful daylight illuminance. These new metrics complement the daylight factor values, describing the daylight inside a room [13].

However, neither the daylight factor nor dynamic metrics fully describe the quality of natural light, because all of these metrics represent the quantification of light only for the visual system. Therefore, it is necessary to define a metric related to the non-visual human response to light, the human circadian system [14].The circadian stimulus is a metric which can help predict daylighting's benefits on human health [15], [16]. Using a model of photo transduction [17], the circadian light can be defined according to the daylight allowed by windows or clerestories.

Daylight is potentially the ideal light source for synchronizing our circadian systems to local time. It provides the right amount for circadian entrainment. Indeed, for millennia this was the only light source used by terrestrial species for circadian entrainment. In a modern, 24 hour 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 during night, blurs the distinction between day and night, compromising our entrainment to the local time [18]. In other words, without access to daylight (or electric lighting providing comparable amount, spectrum, distribution, duration, and timing), human health and well-being may be compromised. Although daylight may help patients in hospitals or care rooms [19], [20], studies to date have investigated the effect of daylight on patients' outcomes [21, 22], but have not specifically investigated the effects of daylight on the circadian system of occupants in common residential rooms according to window design.

II. Objectives

The main aim of this research is to determine the impact of the window size and room reflectance to deliver a proper circadian stimulus (CS) value enough to promote entrainment in educational spaces.

A first trial is carried out, analyzing the spectral power distribution (SPD) perceived for the eyes of the students, according to the window orientation and the observer's field of view. This trial serves to determine the impact of the field of view in the circadian stimulus, which basically depends on

Manuscript received September 23, 2018; revised April 2, 2019. This work was supported in part by the University of Seville.

The authors are with University of Seville, Spain (e-mail: iacosta@us.es).

DOI: 10.7763/IJET.2019.V11.1131

the SPD perceived and the amount of light received by the pupils.

The second trial analyzes the circadian stimulus inside a classroom promoted by daylighting, according to different variables, such as the window size and its position, as well as the variable reflectance of the inner surfaces of the room.

III. Methodology

A. Model

In accordance with most common classroom design, a virtual room 3.0 m high by 8.0 m deep by 8.00 wide is defined. The room has one window located on the facade, considering 7.0 m long with a variable height. The double pane window was 0.05 m thick with a visible transmission of 0.75. The window lintel was 0.25 m thick, as were the sill and jambs. All variables of the calculation model are shown in Fig. 1.

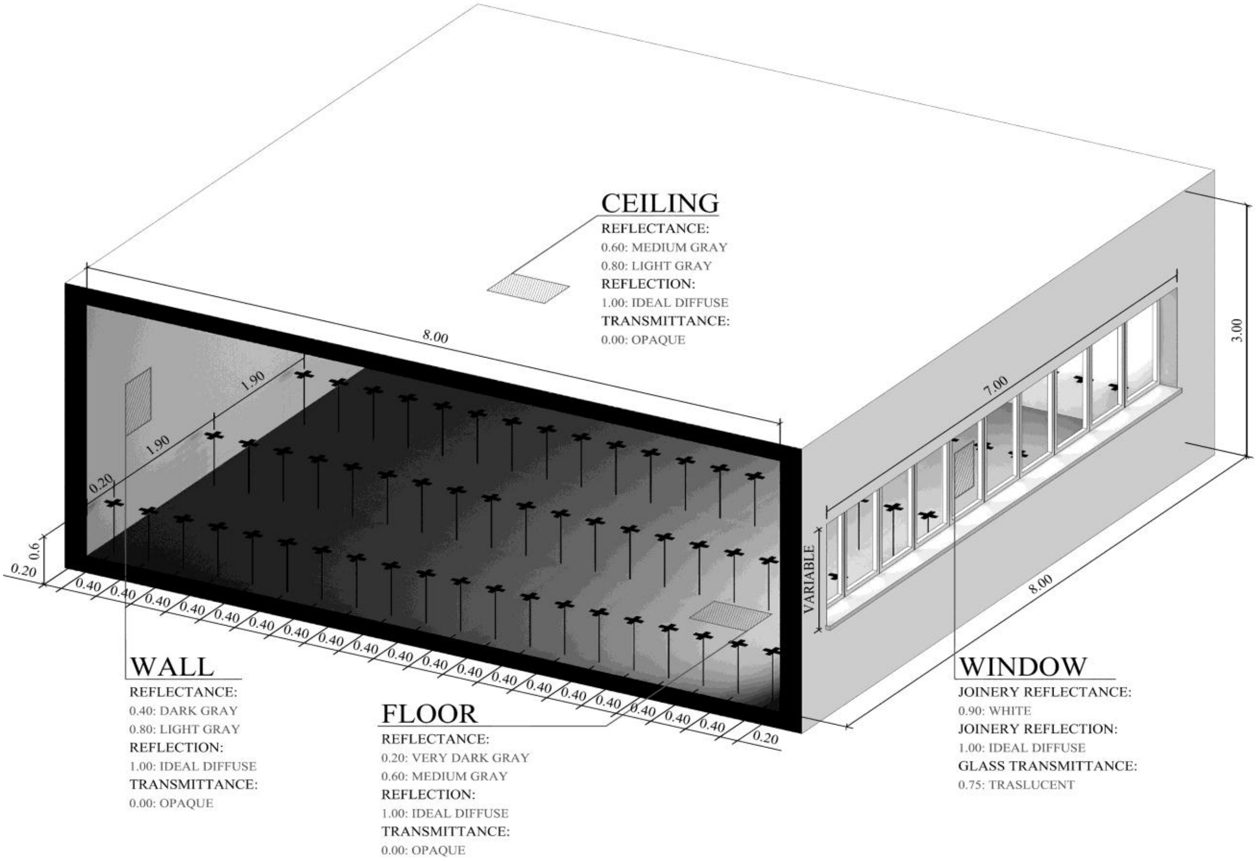

Fig. 1. Classroom model.

The measurement of circadian stimulus is performed on the axis of symmetry of the calculation model and on three equidistant axes at 1.00 m. Therefore, the study points are located on these axes with a spacing of 0.40 m and a height above ground of 0.60 m.

B. 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 [23] 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 originally provided by RADIANCE. This lighting software has been validated by several researchers [24, 25] who have determined accuracy by applying the CIE test cases [26]. The calculation parameters used by this program in this research are shown in Table I.

TABLE I: Calculation Parameters of DaySim 3.2

Radiance Simulation Parameters	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

C. Sky *Conditions*

The location of the room model correspond to London, UK at 50º north latitude under predominantly overcast skies. All trials relating to size of the window are developed under these weather conditions.

Weather data for are taken from the Energy Plus reference [27], based on direct normal and diffuse horizontal irradiances and the sky model defined by Perez et al. [28].

D. Calculation Conditions

The calculation of circadian stimulus have been developed considering an occupancy hours from 8:00 am to 3:00 pm, with one break to lunch. The illuminance threshold to meet a value of 50% is 522 lux. The blind control is active, so the users avoid direct sunlight on work plane.

In order to determine the CS values, Rea et al.'s model of photo transduction by the human circadian system was used to estimate CLA from the source spectral power distribution (SPD) and the illuminance levels obtained at each study point, 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 the duration of exposure of 1 h.

IV. First Trial

The variation of the spectral distribution perceived on the eyes of the observer can vary according to the angle of vision, so it is important to determine the effect of the field of view in the CS calculation. Accordingly, two trials have been carried out, in two different classrooms of the High School of Architecture of Seville, Spain. The first classroom is facing north while the second classroom is oriented to south.

The aim of this trial is to quantify the different SPD results depending on the field of view and the orientation of the windows.

Both classroom have similar reflectance values in floor, walls and ceiling, as well as in the work plane, which is white. The window to façade ratio is close to 35% for both case-studies.

The measurements were taken during the morning, from 11:00 am to 12:00 pm, from June 20 to 25.

Fig. 2. Measures looking at the table (angle 0°), looking at the back of the chair in front (angle 30°) and looking at the end of the classroom (angle 60°) for the venue with windows facing north.

In order to determine the SPD quantification, as well as the reflected illuminance from the environment, a spectrometer Konica Minolta CL-70F was used. The measures were carried out 40 cm above the table, considering the typical location of the eyes of an observer sitting in a chair. Three measures were taken in each classroom, considering different angles of vision: looking at the table (angle 0°), looking at the back of the chair in front (angle 30°) and looking at the end of the classroom (angle 60°). Fig. 2 and 3 shows the measurements on the studied points.

Fig. 3 Measures looking at the table (angle 0°), looking at the back of the chair in front (angle 30°) and looking at the end of the classroom (angle 60°) for the venue with windows facing south.

The spectral distributions measured in the classroom facing north are shown in Fig. 4. As can be seen, the spectrums perceived have a similar distribution, with a peak between 456 and 457 nm.

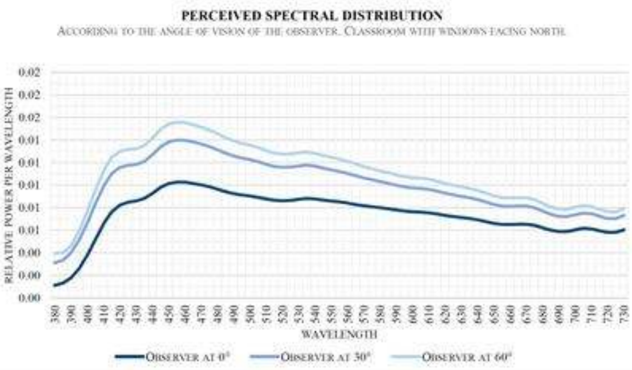

Fig. 4. Perceived spectral distribution depending on angle of vision. Classroom with windows facing north.

Each SPD produce a different illuminance value, as well as a different melatonin response. Table II shows the illuminance values and the circadian stimulus according to the defined SPD and the photo transduction model by Rea et al.

TABLE II: Illuminance Values and Circadian Stimulus Provided By the Perceived Spectrums. Windows Facing North

Angle of vision	0°	30°	60°
E	644 lx	794 lx	871 lx
CS	53.8%	57.2%	58.5%
CCT	6649 K	7094 K	7220 K

As seen in Table II, the difference between different fields of view barely affects to the melatonin suppression. In the study case of the classroom with windows facing north, the CS varies from 53.8% to 58.5%, considering the measurements conditions. Therefore, the CS variation is lower than 5%, considering the methodology and the boundary conditions described.

The spectral distributions measured in the classroom facing south are shown in Fig. 5. As can be seen, the spectrums perceived have a similar distribution, with a peak of 461 nm for all measures.

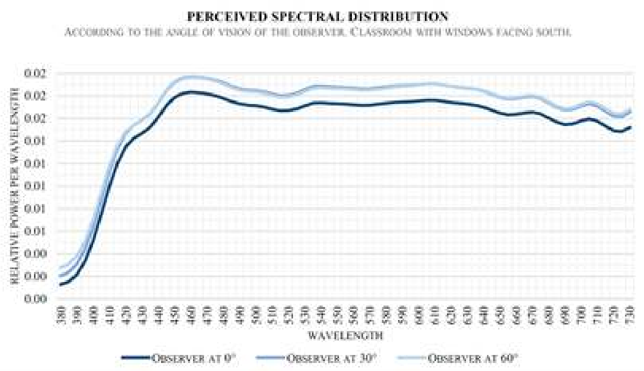

Fig. 5. Perceived spectral distribution depending on angle of vision. Classroom with windows facing south.

Fig. 6. Exterior spectral distributions. Classroom with windows facing north and south.

As in the previous case, Each SPD produce a different illuminance value, as well as a different melatonin response. Table III shows the illuminance values and the circadian stimulus according to the defined SPD and the phototransduction model by Rea et al., considering the room model with windows facing south.

TABLE III: ILLUMINANCE VALUES AND CIRCADIAN STIMULUS PROVIDED BY THE PERCEIVED SPECTRUMS. WINDOWS FACING SOUTH

Angle of vision	0°	30°	60°
E	1260 lx	1360 lx	1361 lx
CS	59.7%	60.0%	60.1%
CCT	5343 K	5328 K	5315 K

As can be deduced, the variation of CS is almost null, since the minimum illuminance measure, taken looking at the table (angle 0°), produces a CS of 59.7%, while the higher value diverges less than 1%. Accordingly, the variation of the CS value depending on the field of view is negligible for the case of a classroom with windows facing south.

There is a variation between the CS values produced in both classrooms (there is difference between 2 and 6%, depending on the angle of view). However, that variation is generated mainly by the illuminance value. In fact, introducing the illuminance value determined for the observation angle of 60° with windows facing south (1360 lx) in the case of the observation angle of 0° with windows facing north, the CS promoted is almost the same. Therefore, the illuminance is playing a more important role than SPD for determining the CS value under these conditions.

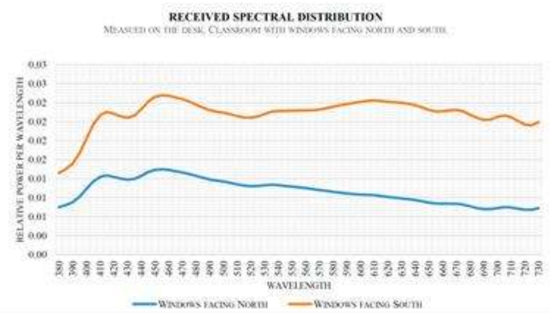

Fig. 7. Received spectral distributions on the studied desks. Classroom with windows facing north and south.

The final analysis of the first trial quantifies the comparison between the received and reflected SPD on the work plane. The SPD of the skies have been measured for both classrooms, as can be seen in Fig. 6.

The daylight spectrum measured on the desk will serve to determine an approach of the spectral reflectance of the table. Fig. 7 shows the SPD measured on the study desks.

Knowing the SPD received and reflected by the studied work plane, a first approach can be carried out to determine the spectral reflectance of the table. As can be deduced, this procedure is not so much accurate as using a specific colorimeter, but it can be useful for an estimation of the surface qualities of the desk. Fig. 8 shows the estimation of spectral reflectance of the desk, according to both classrooms.

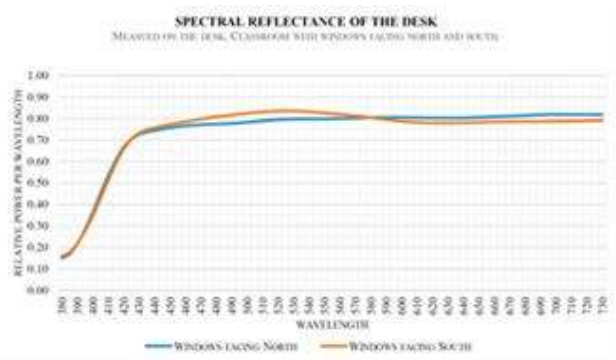

Fig. 8. Spectral reflectance of the studied desks. Classroom with windows facing north and south.

As can be seen in Fig. 8, the spectral reflectance of the table is really close in both study cases. This point demonstrates that the reflectance of the table barely varies, regardless the SPD of the light source received. This affirmation is true for the case of daylight SPD, which are particularly broad along the visible spectrum.

V. SECOND TRIAL

Once determined the effect of the window orientation and the observer's field of view in the quantification of CS, a second trial is carried out, defining the CS measure depending on the window size and position, as well as the reflectance of the inner surfaces.

This second trial is based on the calculation program DaySim 3.1, described in the methodology.

Fig. 9 shows the average CS values throughout the year, considering a window to façade ratio of 30% and a variable position of the opening. Two inner reflectances have been considered for this trial (bright, and dark, as defined in Figure 1) and three different work planes (white, light wood and pale blue).

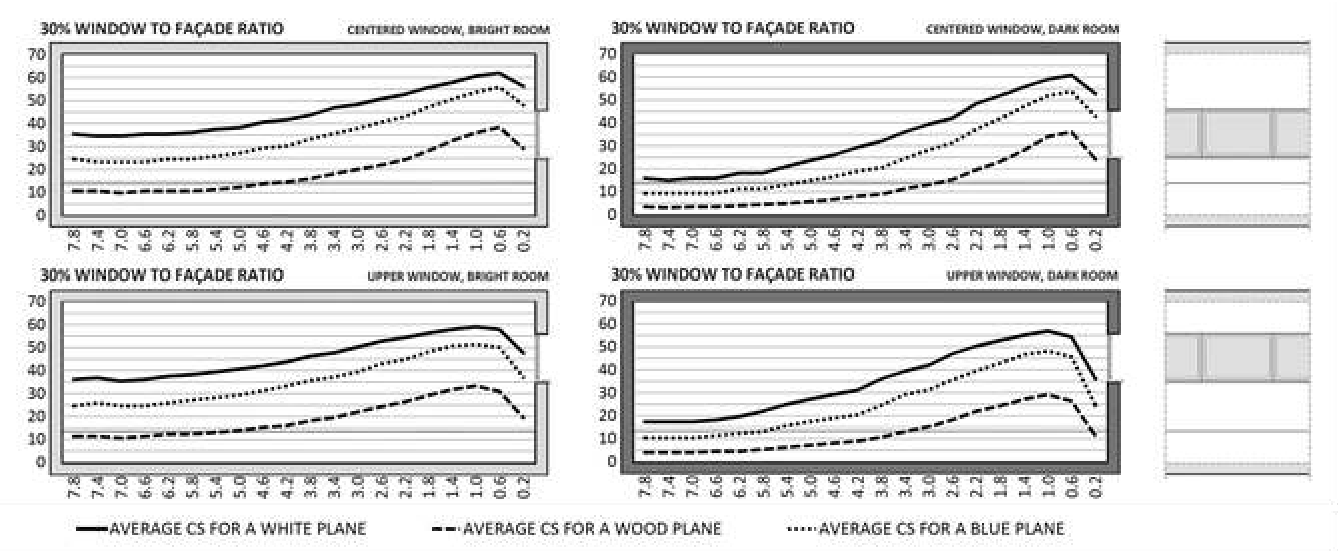

Fig. 9. Average circadian stimulus for a window to façade ratio of 30%.

Figure 10 represents the average CS values for the same case-study, considering a window to façade ratio of 60%. As can be deduced from figures, the room sections show the average CS from 0 to 70%, according to the distance from the façade. The window size varies from 30 to 60%, while its position is considered centered in the facade or in an upper position, considering a sill 1.5 m high.

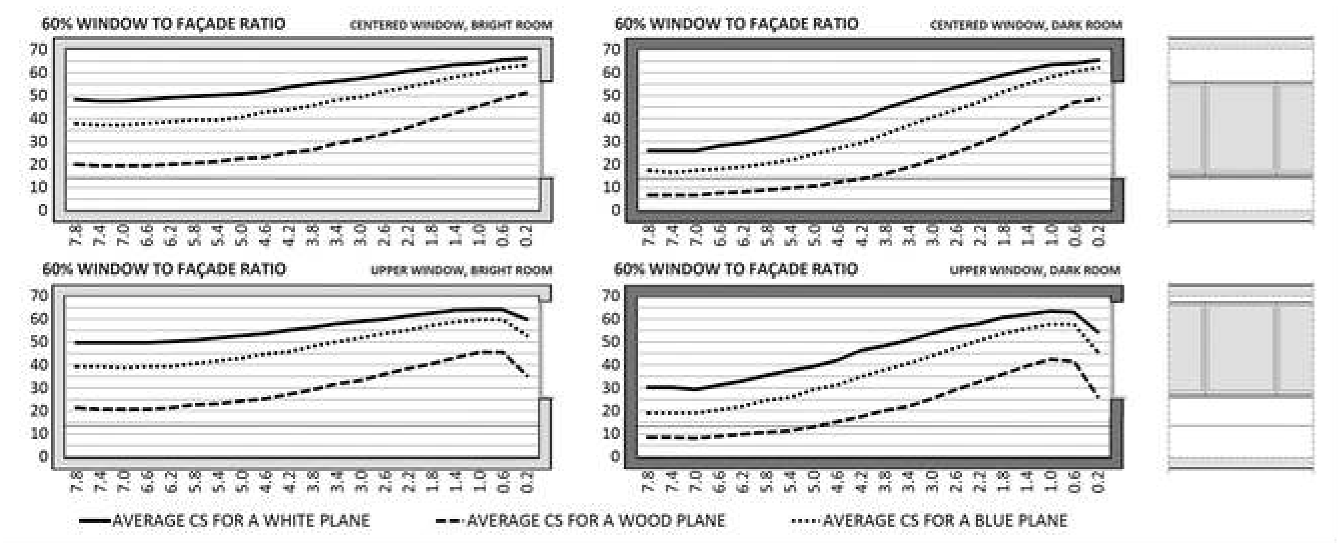

Fig. 10. Average circadian stimulus for a window to façade ratio of 60%.

As can be seen, the average CS values are higher in the area close to the window, gradually decreasing toward the back of the room and following a similar tendency to the average illuminance values. As deduced from Figures 9 and 10, the resulting CS and the window area are not directly proportional. However, a linear tendency can be determined comparing the CS values from the two window sizes.

It should be noted that the reflectance of the inner surfaces plays an important role for determining the CS value in the back of the classroom. As deduced from Figures 9 and 10, the CS results are up to 200% higher for classrooms with bright surfaces in comparison with dark venues.

The color of the perceived work plane has a noticeable impact on the light and spectrum received by the student's eyes, therefore a high variation of CS can be observed. The white desk produces an average CS value near 40% higher than that of the pale blue plane, varying in accordance with the window to façade ratio and the reflectance values of the inner surfaces. Compared to the light wood plane, the white desk allows an increase of the average CS close to 200%.

VI. Conclusions

The analysis of results has assessed the variation of the circadian stimuli, which determines the synchronization of the circadian rhythm, depending on the geometry of the opening, reaching several conclusions that can be applied to window design. Additionally, the study of the variation of the reflectance of the inner surfaces of the room allows determining the circadian stimulus based on this variable.

The quantification of the circadian stimulus serves as a basis for the analysis of results. However, it also offers a database of the natural illumination produced by a window within a room. Accordingly, the most representative calculation models of current architecture have been chosen for simulation, using the most common window designs. Obviously, this research does not cover all possible hypotheses, but aims to show the most frequent cases study under the most adverse sky conditions.

This research demonstrates the noticeable impact of the reflectance values, not only from the inner surfaces of the classroom, but also from the work plane perceived by the students.

REFERENCES

[1] S. Treado, G. Gillette, and T. Kusuda, "Daylighting with windows, skylights, and clerestories," *Energy and Buildings*, vol. 6, 1984, pp. 319- 330.

[2] D. H. W. Li, "A review of daylight illuminance determinations and energy implications," *Applied Energy*, vol. 87, 2010, pp. 2109-2118.

[3] I. Acosta, C. Munoz, M. A. Campano, and J. Navarro, "Analysis of daylight factors and energy saving allowed by windows under overcast sky conditions," *Renewable Energy*, vol. 77, 2015, pp. 194-207.

[4] C. M. Munoz, P. M. Esquivias, D. Rangel, I. Acosta, and J. Navarro, "Climate-based daylighting analysis for the effects of location, orientation and obstruction," *Lighting Research and Technology*, vol. 46, 2013, pp. 268-280.

[5] H. H. Alzoubi and A. H. Al-Zoubi, "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*, vol. 51, 2010, pp. 1592-1599.

[6] A. Villalba, A. Pattini, and E. Correa, "An approach to urban tree daylight permeability simulation using models based on louvers," *Building and Environment*, vol. 73, 2014, pp. 75-87.

[7] L. Sanati and M. Utzinger, "The effect of window shading design on occupant use of blinds and electric lighting," *Building and Environment*, vol. 64, 2013, pp. 67-76.

[8] P. R. Boyce, "The impact of light in buildings on human health," *Indoor and Built Environment*, vol. 19, 2010, pp. 8-20.

[9] CIE, International lighting vocabulary, Commission Internationale de l'Éclairage, 2011, CIE S 017:2011.

[10] CIBSE, Daylighting and Window Design, CIBSE LG10. London: Chartered Institution of Building Services Engineers, 1999.

[11] J. A. Love, "Determination of the daylight factor under real and overcast skies," *Journal of the Illuminating Engineering Society*, vol. 22, no. 2, 1993, pp. 176-182.

[12] C. F. Reinhart, J. Mardaljevic, and Z. Rogers, "Dynamic daylight performance metrics for sustainable building design," *Leukos*, vol. 3, no. 1, 2006, pp. 7-31.

[13] P. R. Boyce and K. A. G. Smet, "LRT symposium "Better metrics for better lighting," *A Summary, Lighting Research and Technology*, vol. 46, 2013, pp. 619-636.

[14] R. P. Leslie, L. C. Radetsky, and A. M. Smith, "Conceptual design metrics for daylighting," *Lighting Research and Technologies*, vol. 44, 2012, pp. 277-290.

[15] M. G. Figueiro, J. A. Brons, B. Plitnick, B. Donlan, R. P. Leslie, and M. S. Rea, "Measuring circadian light and its impact on adolescents," Lighting Research and Technology, vol. 43, 2011, pp. 201-215.

[16] A. Barroso, K. Simons, and P. Jager, "Metrics of circadian lighting for clinical investigations," *Lighting Research and Technology*, vol. 46, 2014, pp. 637-649.

[17] M. S. Rea, M. G. Figueiro, J. D. Bullough, and A. Bierman, "A model of phototransduction by the human circadian system," *Brain Research Reviews*, vol. 50, no. 2, 2005, pp. 213-228.

[18] I. Acosta, R. Leslie, and M. G. Figueiro, "Analysis of circadian stimulus allowed by daylighting in hospital rooms," *Lighting Research and Technology*.

[19] I. Kriszbacher, J. Bódis, I. Boncz, A. Koppan, and M. Koppan, "The time of sunrise and the number of hours with daylight may influence the diurnal rhythm of acute heart attack mortality," *International Journal of Cardiology*, vol. 140, 2010, pp. 118-120.

[20] J. D Bullough, M. S. Rea, and M. G. Figueiro, "Of mice and women: Light as a circadian stimulus in breast cancer research," *Cancer Causes and Control*, vol. 17, 2006, pp. 375-383.

[21] H. H. Alzoubi and S. M. Al-Rqaibat, "The effect of hospital design on indoor daylight quality in childrensection in King Abdullah University hospital, Jordan," *Sustainable Cities and Society*, vol. 14, 2014, pp. 449-455.

[22] J. H. Choi, L. O. Beltran, and H. S. Kim, "Impacts of indoor daylight environments on patient average length of stay (ALOS) in a healthcare facility," *Building and Environment*, vol. 50, 2012, pp. 65-75.

[23] R. Perez, R. Seals, and J. Michalsky, "All-weather model for sky luminance distribution - Preliminary configuration and validation," *Solar Energy*, vol. 50, no. 3, 1993, pp. 235-245.

[24] C. F. Reinhart and O. Walkenhorst, "Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds," *Energy and Buildings*, vol. 33, no. 7, 2001, pp. 683-697.

[25] I. Acosta, C. M. Munoz, P. M. Esquivias, D. Rangel, and J. Navarro, "Analysis of the accuracy of the sky component calculation in daylighting simulation programs," *Solar Energy*, vol. 119, 2015, pp. 54-67.

[26] CIE, Test cases to assess the accuracy of lighting computer programs, Commission Internationale de l'Éclairage, 2006.

[27] Lawrence Berkley National Laboratory, EnergyPlus Engineering Reference. The reference to EnergyPlus Calculations, Lawrence Berkeley National Laboratory, Technical report , 2012.

[28] CIE, Spatial Distribution of Daylight - CIE Standard General Sky, Commission Internationale de l'Éclairage, 2003.

I. Acost is a professor at the Department of Building Construction, University of Seville, Spain. He is member of the research group TEP-130 which is focused on sustainability, energy efficiency, lighting and acoustics related to building design.

The author belongs to the Instituto Universitario de Arquitectura y Ciencias de la Construcción.

The main research field of the author is the study of daylighting and its relationship with the architectural design. Most of the papers developed by the author analysis the energy savings in electric lighting produce by the proper use of daylighting, the study of predictive methods to determine the illuminance in courtyards and the measurement of the circadian stimulus.

M. A. Campano is a professor at the Department of Building Construction I, University of Seville, Spain. He is a member of the research group TEP-130, which is focused on sustainability, energy efficiency, lighting, acoustics and optics related to building design and heritage refurbishment.

He develops research on the field of energy efficiency, indoor environmental comfort and daylighting, as well as their relationship with the architectural design.

J. F. Molina is a postdoctoral researcher in the Department of Architectural Graphic Expression at the University of Seville, Spain. He is member of the research group HUM-799, focused on sustainability architectural heritage and design.

J. Fernández-Agüera is a postdoctoral researcher in Department of Building Construction I at the University of Seville, Spain. She is a member of the research group TEP-130. Her research focuses on energy efficiency, low-energy buildings, airtightness, indoor air quality and ventilation, with special interest in the interaction between environmental parameters, health and thermal comfort in dwellings.