PAPER • OPEN ACCESS

Occupant perception of spectral light content variations due to glazing type and internal finish

To cite this article: J Potočnik *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* 296 012033

View the article online for updates and enhancements.

Occupant perception of spectral light content variations due to glazing type and internal finish

J Potočnik[1], J D B Cadena[2,*], M Košir[1] and T Poli[2]

[1]Chair of Buildings and Constructional Complexes, Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova 2, SI-1000 Ljubljana, Slovenia
[2]Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, via Ponzio 31, 20133 Milano, Italy

* juandiego.blanco@polimi.it

Abstract. Indoor Environmental Quality (IEQ) is a key issue in the design and renovation of any indoor building environment. It is comprised of different aspects (e.g. visual, thermal, acoustic comfort, etc.), which directly affect the building occupants' wellbeing. Studies on this topic have grown rapidly in recent years, as the time that occupants spend indoors is increasing. In this regard, indoor luminous conditions are crucial for providing sufficient task illuminance as well as to stimulate the human circadian system. Insufficient lighting conditions have been proven to be related with reduced productivity/learnability, mood swings and health disorders, thus emphasizing the necessity for further research in this field. Therefore, proper performance evaluation criteria for managing and optimizing lighting spectral composition is needed. For instance, indoor lighting conditions can be evaluated by quantity, intensity, and/or uniformity, but also by spectral content, which determines the energy conveyed and the level at which the human body is stimulated. This spectral content can vary depending on the preferred or prevalent light source, interior finishes and glazing properties generating a singular indoor lighting environment. Thus, a preliminary study on the variation of the indoor daylight spectral content is conducted using a scaled model, applying various glazing types and interior finishes. Then, daylight simulations are performed on a calibrated virtual model to evaluate the effect of various environmental conditions. Results show a considerable impact of the interior finishes as well as glazing type on the attained circadian potential of studied indoor environment.

1. Introduction

It is becoming exceedingly acknowledged that light induces not only visual responses but also non-visual, photo-biological responses on human body. Exposure to light, particularly to daylight, is crucial for maintaining circadian rhythms, since it directly affects the internal biological clock in the Super Chiasmatic Nuclei (SCN) [1]. The latter is responsible for regulating body temperature, melatonin and serotonin secretion, etc. If the functioning of the SCN is disrupted, it can cause potential health issues like fatigue, sleep disorders, increased risk of cancer, etc. [2][3]. Furthermore, inappropriate luminous conditions (i.e. intensity and/or spectral composition) might also cause changes in alertness, performance and mental wellbeing [4][5][6]. Circadian photo-transduction is predominantly enabled by the photo-pigment Melanopsin [7] located in the intrinsically photosensitive Retinal Ganglion Cells (ipRGC). Contrary to the human visual system response (light transduced by cones and rods), which has a peak sensitivity at 555 nm. The circadian system's response to light peaks at shorter wavelengths of the visible spectrum [8][9][10]. Therefore, if a human is exposed to light with a richer blue spectrum, the light has an advancing and more pronounced effect on the circadian system than blue diminished

light. Overall, the circadian response to light is exceedingly complex, as in addition to the spectral composition and intensity of light source, also the exposure timing plays a considerable role in activating the appropriate body responses. This complexity of results in the situations where the same amount of light stimuli in the morning hours may maintain our 24-hour biological cycle, while on the other hand the same stimuli received during the evening may disrupt it. In order to facilitate the assessment of the described non-visual impact of light, several metrics have been introduced in recent years. The most widely used is the Circadian Stimulus [11], expressing biologically weighted effects and the weighted luminous values expressed through melanopic lux [12]. Despite extensive research done in this field during the last two decades, an absolute quantity, quality and timing of "the healthiest" light exposure has not yet been defined.

It is evident that the introduction of electrical lighting induced a drastic decrease in time spent outdoors by the building occupants. This resulted in the increased possibility that building occupants will become disconnect with the Earth's day and night cycle. Daylight in particular has been demonstrated as superior "zeitgeber" (i.e. timer) for our circadian system and cannot be simply replaced by artificial luminaires [13]. It was shown through a field study investigating luminous conditions in spaces for dementia suffering persons, conducted by Konis [14], that better day lit spaces offer greater circadian potential than poorly day lit ones with additional artificial luminaires. Hence, it is essential to assess indoor luminous properties of received daylight in the context of buildings, because various architectural characteristics (e.g. room geometry, window size, material properties, etc.) will affect the potential for circadian daylighting. In particular, internal surface reflectance seems to have a significant impact on the circadian potential of a particular indoor environment, as established by Cai et al. [15]. They demonstrated that change in corneal illuminance is significantly affected by interior surface reflectance and to a lesser degree by glazing type properties. Specifically, differently coloured walls with the same average reflectance have dissimilar impacts on the resulting circadian potential (e.g. blue wall colour maintains higher melanopically weighted illuminance than red colour) [16]. Although glazing properties have smaller impact on the circadian potential, it was shown by Hraška et al. [17] that patients in hospital rooms with amber coloured windows produced more melatonin than patients in rooms equipped with spectrally neutral glazing.

The research body on the topic of the circadian potential in buildings is quite extensive. Nevertheless, it is still not clear to what degree the glazing light transmittance properties and indoor colour finish selection impact the quantitative (i.e. illuminance levels) and particularly the qualitative (i.e. spectral composition resulting in melanopically weighted light levels) aspects of indoor luminous environment. Furthermore, even when the stated features are investigated, they are usually only simulated and/or studied in the context of case specific environments [18], thus limiting the potential for extrapolating generic patterns from the derived results. In this respect, the main objective of the presented study is to experimentally evaluate the exerted impact of various glazing types and wall colours on the spectral composition and illuminance levels of indoor daylight at eyelevel of a hypothetical occupant. In addition to the experiments, a calibrated virtual model will be developed for the purpose of evaluating visual and circadian daylighting aspects under standardized conditions (i.e. CIE standard sky types and illuminants).

2. Methodology

The evaluation of the quantitative and qualitative aspects of indoor luminous environment under different conditions of spectral wall reflectance and glazing spectral transmittance was executed using experimental measurements and calibrated computer simulations. The experimental results acquired under real world conditions on a scaled model of a typical cellular office were used to develop and validate the simulation model built using Rhinoceros and Grasshopper algorithm for Honeybee [19] and Lark [16] plug-ins enabling the evaluation of the visual and circadian daylighting. The model enables the analysis of the indoor luminous environment under different standardised conditions, thus offering a far greater flexibility than real life experiments. This means that simulations can be used to evaluate the effect of further configurations under standardised CIE sky conditions at far greater speed and lower cost.

2.1. Experimental setup

The experimental scale model (600 x 800 x 520 mm) is a representation of a small office at a scale of 1 to 5, corresponding to a real life size room of 3 by 4 by 2.6 m (Figure 1) oriented towards north. The scale model is equipped with a single north oriented window opening of 280 by 180 mm (i.e. real-life size of 1.4 x 0.9 m), resulting in a window to wall ratio of 16 % and window to floor ratio of 10.5 %. Internal wall and ceiling surfaces were painted white, floor was left untreated (natural wood). For the purpose of the experiments, three different glazing types were used, while the impact of internal spectral colour reflectance on the luminous environment was investigated by changing the colour of the east internal wall only. Optical material properties of indoor surfaces, and the exterior ground surface, are presented in Table 1. Opaque material surface reflectance (R_{vis}) and glazing light transmittance in the visual spectrum (τ_{vis}) were determined using the spectrophotometer measurements.

Table 1. Optical material properties of the experimental scale model and virtual model. For the blue, orange and grey wall colours the L*a*b* colour space coordinates are also presented.

Opaque surface	R_{vis}	Glazing type	τ_{vis}
White wall and ceiling [a]	0.87	Double pane, without coatings [b]	0.80
Wooden floor [a]	0.61	Double pane with low-e	0.76
Blue wall (L*a*b*: 76, -4, -23)	0.59	Triple pane with low-e	0.46
Orange wall (L*a*b*:77, 24, 44)	0.56		
Grey wall (L*a*b*: 76, 0, 0)	0.54		
Exterior ground [a]	0.20		

[a] *Constant in all scenarios (except for east-wall)*

[b] *Constant only for second cycle experiments and simulations*
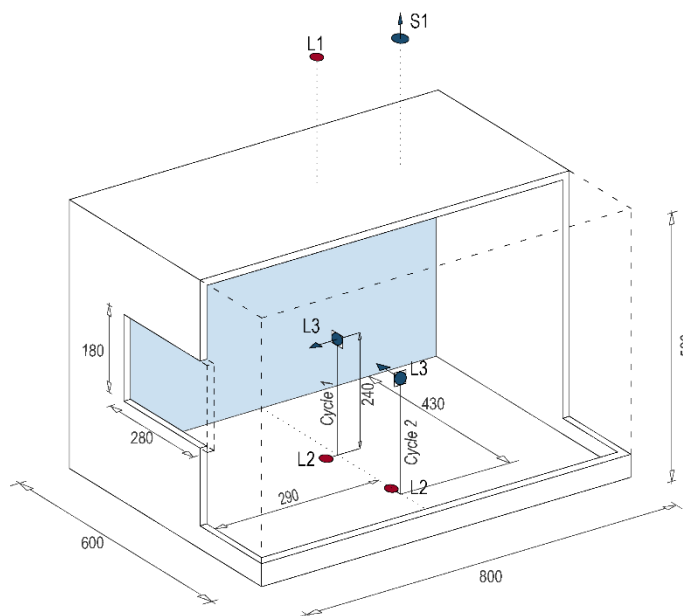

Figure 1. The geometry of the scale model and the experimental measurements setup. The coloured internal wall marks the internal surface, the spectral reflectivity of which was varied during the second cycle experiments.

In order to evaluate the indoor luminous environment, the illuminance and spectral irradiance data were collected simultaneously. As shown in Figure 1, illuminance was recorded at three positions – rooftop sensor (L1) measuring global illuminance (E_{Eh}), interior sensor (L3) at 240 mm of height measuring vertical illuminance (E_{Iv}) and interior horizontal sensor (L2) recording the illuminance (E_{Ih}) on the floor level. The melanopic lux values (E_M) were calculated using Irradiance Toolbox developed by Lucas et al. [20] with measured E_{Iv} values as input. Illuminance values were recorded, using Almemo FLA603-VL4, $V(\lambda)$ calibrated lux meters (absolute error ±1 lx) connected to Almemo 5690-2 data logger [21], for simultaneous measurement and recording of data at all positions. Spectral irradiance

data in the visible spectrum (380 – 780 nm) were acquired by two calibrated StellarNet BLACK-Comet [22] concave grating spectrometers at 1.5 nm spectral resolution at two positions. The first spectrometer (position S1 in Figure 1) was positioned outside the model, pointing towards the sky, with an unobstructed view recording sky spectral irradiance data. The second one was coupled with the illuminance sensor at position L2 (Figure 1), measuring internal vertical spectral composition of daylight.

Experimental data were collected during 30th of January 2019 in Ljubljana, Slovenia (lat.: 46.05°N, long.: 14.5° E) at an unobstructed location (rooftop of the Faculty of Civil and Geodetic Engineering building) with predominantly intermediate sky conditions throughout the experiment. Due to the changeable nature of daylight, each of the model variations was continuously measured for 2 minutes and a median value was derived for each interval recording. The experiment was carried out in two cycles:

- The first cycle was executed between 9:20 and 9:40 am, with L3 sensors facing the window (Figure 1). The internal surface reflectance was fixed during the first cycle measurements, while the glazing types were varied (Table 1).
- The second cycle took place between 11:50 am and 12:23 pm, with L3 sensors facing the east internal wall (Figure 1). During the second cycle measurements, the glazing properties were fixed (i.e. double pane glazing without coatings, see Table 1), while the surface spectral reflectance of the eastern wall was varied by applying white, blue, orange and grey wall coatings (Table 1).

2.2. Simulation model and presumption

The virtual model was created with Rhinoceros v5 based on the dimensions of the experimental scale model, including the position at which it stands over the ground. In order to consider the reflected rays coming from the rooftop's ground surface, its reflectance was set at R_{vis} of 0.20 for Red, Blue and Green colour channels, whereas the influence of other obstructions was ignored. Following the completion of the geometric model, the Radiance model was built for the foreseen simulations using built-in functions comprised within Grasshopper and specific Honeybee and Lark plug-ins. In order to obtain accurate simulation results, the sky must be modelled appropriately. Thus, a custom CIE_{BR} sky [23] was created with the Radiance sky description generator *gensky* -B -R option, for each scenario and time step. The generated sky was modelled as either intermediate or overcast (depending on the weather conditions of the simulated day), while its intensity was defined by the direct and diffuse irradiance data obtained from Slovenian Environment Agency [24] for the calibration simulations, or from the EPW file for Ljubljana [25] for the simulations with the generic weather conditions. All simulations were done under the Daylight Coefficient (DC) method (with medium quality settings), implemented inside Radiance with ambient bounce (–ab) parameter set at 3.

Material spectral properties of the virtual model were defined according to the experimentally determined R_{vis} and τ_{vis} and using the specific Lark component, which delivered the primitive *void plastic* and *void glass* material type [26] for all surfaces, with a specific R_{vis} for each colour channel without specularity and/or roughness assigned. Similarly, the non-monochromatic sky was created using one of the components offered by Lark, requiring a normalized illuminant spectrum for defining the spectral composition of the light generated by the source (i.e. sky), diffuse and direct horizontal radiation with the E_{Eh} at the specific moment computed by an initial Radiance analysis. For the model calibration simulations, the measured spectral composition of total exterior daylight was used as input, while for other simulations a standard D65 illuminant composition was assumed. Because the simulation analysis was focused on the study of generic environmental conditions, a preliminary analysis of the weather data was performed to identify days with the least/most frequent sky cover and the maximum/minimum global horizontal illuminance.

Lark is designed to split the traditionally analysed monochromatic light into different channels (9 channel analysis was used in this work to assure greater accuracy [18]), each channel representing a different portion of the visual spectrum. Consequently, each channel requires a Radiance analysis tracing the light rays across the modelled domain and estimating the quantity of light that strikes the analysed test points L2 and L3 (Figure 1). Grid-based illuminance analysis was executed for the L2, while the

image-based luminance analysis was carried out for the L3 test point for each time step and specific glazing and wall finish configuration. As final simulation outputs, the values of illuminance levels (E_{Ih} and E_{Iv}) and circadian daylighting potential expressed in melanopic lux were calculated.

It is important to acknowledge that the use of medium quality, and $-ab = 3$, might result in difference between the simulated values reported herein, and the experimentally measured ones under the same conditions. However, these deviations can be tolerated as more granular analysis would considerably increase the required computational time. Furthermore, the use of a unique standard illuminant (i.e. D65) for the light source spectral composition, and the assumption of a monochromatic reflectance of the external ground surface, introduce further uncertainties in the simulation results. In addition, the scaling of the model might also affect the results, because smaller size of the calculation domain might limit the allowance of ray influx. Nevertheless, the scope of this work was not focused on the determination of exact quantity of light falling on the test points, or amount of stimulus generated at the eye level for the specific gaze direction, but on the relative impact that the variance of the glazing and interior surface finishing properties might have. Therefore, the virtual model performance was evaluated according to the ratios E_{Eh}/E_{Ih} and E_{Eh}/E_{Iv}, while the use of a standard illuminant source type becomes convenient, because it enables simulations without time consuming experiments that are dependent on case specific weather conditions.

3. Results

This section presents separately the conducted simulation and the experimental results. The experimental data regarding the impact of the glazing spectral transmittance and indoor wall finish spectral reflectivity on the luminous environment of the scale model will be presented through the measured illuminances as well as spectral composition of daylight. For the simulation part, firstly the validation of the virtual model in relation to the experimental results will be presented. Secondly, the calibrated model was used to simulate indoor conditions during extreme days of the year adopting standardised weather files and CIE sky types with CIE D65 illuminant. Therefore, the simulations' results provide a more generic overview of the impact of the studied parameters on the achieved indoor luminous conditions.

3.1. First cycle experiments

For the first cycle experiments, executed between 9:20 and 9:40 am on the 30th of January 2019, the test point L3 was positioned at the centre of the scale model facing the window (Figure 1). Placement of the L3 test point corresponds to a sited hypothetical occupant with an eye high of 1.20 m positioned 1.45 m from the external wall, with a view oriented directly towards the window. The internal surfaces were kept neutral during the first cycle experiments, with white walls and ceiling ($R_{vis} = 0.87$) and floor in natural wood finish ($R_{vis} = 0.61$), while the orientation of the window was due north. During the entire period of the first cycle experiments the sky conditions were intermediate with external global horizontal illuminance (E_{Eh}) measured at test point L1 in the range between 17 and 26 klx (Table 2), with corresponding spectral composition captured at S1 test point presented in Figure 2. The acquired measurements of illuminance at the analysed test points L1, L2 and L3 are presented in Table 2, while spectral composition of daylight recorded at test points S1 (i.e. spectrometer facing towards the sky) and L3 (i.e. spectrometer facing towards the glazing) are presented in Figures 2 and 3.

The results of the first cycle experiments clearly indicate that the application of spectrally neutral glazing that was investigated during the conducted experiments does not substantially impact the circadian potential of a room, compared to the visual potential. This is evident if the E_M/E_{Iv} ratio is observed in Table 2, where the values close to 1.0 mean that non-visual intensity of daylight expressed through equivalent melanopic lux is comparable to the measured illuminance (i.e. visual impact of daylight). However, in the case of the triple pane glazing with low-e coatings, the impact on non-visual daylight intensity is more substantial, as E_M/E_{Iv} is 0.909 (Table 2). The reason for the greater impact of the triple glazed window is its smaller transmittance at shorter wavelengths, evident from spectral daylight composition captured at the L3 test point and presented in Figure 3. Therefore, the results indicate that the relative impact of glazing on the circadian potential of indoor environment will be mostly due to the spectral transmittance properties of specific glazing and far less due to the overall τ_{vis}

value. In turn, this means that optical properties of applied low-e and spectrally selective films as well as colouring of glass can have an important impact on the achieved indoor circadian potential of a room.

Table 2. First cycle illuminance values and corresponding melanopic lux (E_M [eml]) values measured at the scale model with variable glazing and fixed neutral wall colour.

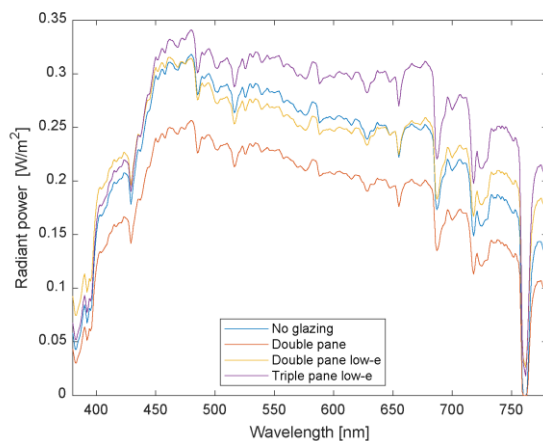| Glazing type	E_{Eh} [lx]	E_{Iv} [lx]	E_{Ih}[lx]	E_{Iv}/E_{Ih}	E_{Iv}/E_{Eh}	E_M [eml]	E_M/E_{Iv}
no glazing	22485.5	2030.0	960.5	2.11	0.090	1986.0	0.978
double pane	18518.0	1481.7	789.0	1.88	0.080	1478.5	0.998
double pane low-e	21392.5	1299.7	679.0	1.91	0.061	1275.5	0.981
triple pane low-e	25487.5	1099.4	549.1	2.00	0.043	999.8	0.909

Figure 2. Spectral composition of total exterior daylight (S1 test point) during the first cycle experiment.
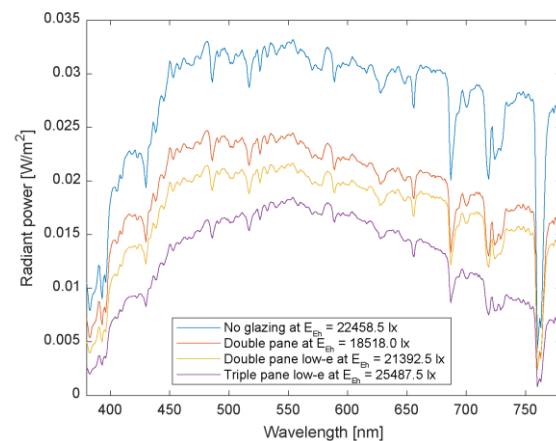

Figure 3. Internal spectral light composition at L3 test point during the first cycle experiment. Note that each measurement was taken at different E_{Eh} (i.e. different time instants), refer to Figure 2.

3.2. Second cycle experiments
During the second cycle experiments conducted between 11:50 am and 12:23 pm on the same day as the first cycle experiments, the influence of changing the colour of one of the internal walls (Figure 1) on the resulting indoor luminous conditions was investigated. In general, the configuration of the experiment was the same as in the case of the first cycle measurements, only the position and the view orientation of the hypothetical occupant were changed. Specifically, the L3 test point was positioned in such a way to simulate a sited occupant 1.45 m from the opening and 2.25 m from the internal east wall, looking directly towards this wall (Figure 1). During the experimental run, the spectral reflectance of the east wall was varied by applying differently coloured papers, while double pane glazing without low-e coating (Table 1) was used for all measurements. The sky conditions throughout the second cycle were comparable to those in the first cycle experimental run (i.e. intermediate sky), with somewhat less cloudy sky. This is observable through more pronounced shorter wavelengths in spectral composition of the total exterior daylight captured at test point S1 (Figure 4). Nonetheless, because the second cycle was executed during midday, the absolute values of E_{Eh} were higher, reaching values between 37 and 53 klx (Table 3).

Observing the results of indoor illuminance values captured at the L2 and L3 test points presented in Table 3, it becomes evident that the spectral reflectivity (i.e. colour) of internal room surfaces have a substantial influence on the achieved circadian potential. This is clearly demonstrated if the ratio between E_M and E_{Iv} for orange coloured wall ($E_M/E_{Iv} = 0.800$) is compared to the grey and white coloured walls ($E_M/E_{Iv} = 0.906$ and 0.982). The latter two wall finishes have a spectrally neutral reflectance, meaning that they reflect approximately the same amount of light regardless of the

wavelength, which means that the spectral composition of reflected daylight is unaffected by the properties of the wall. This, however, is not true for the case of the orange coloured wall, which, as evident from Figure 5, absorbs more light at shorter wavelengths while reflecting more of it at longer wavelengths. Consequently, the non-visual intensity of daylight (E_M) at the L3 test point with orange coloured wall is substantially smaller than the recorded illuminance (E_{Iv}). In effect, this means that for a hypothetical occupant positioned at the L3 test point the orange wall would have a negative effect on the circadian potential of the room in comparison to the spectrally neutral grey wall with comparable R_{vis} (Table 1). A similar conclusion with an opposite effect can be drawn for the blue coloured wall. In this case, high reflectivity at shorter wavelengths (Figure 5) has a positive effect on the resulting E_M mirrored in the highest attained relative non-visual impact ($E_M/E_{Iv} = 1.070$) of all of the studied surfaces (Table 3), because the melanopically weighted illuminance is higher than visually weighted illuminance at lower wavelengths, as presented by [16]. Based on the presented experimental results it can be concluded that the indoor surface spectral reflectivity at comparable values of R_{vis} will have a significant, either positive (e.g. blue wall) or negative (e.g. orange wall), influence on the circadian potential of indoor environments.

Table 3. Second cycle illuminance values and corresponding melanopic lux (E_M [eml]) values measured at the scale model with variable wall colour and fixed glazing (double pane without low-e coating).

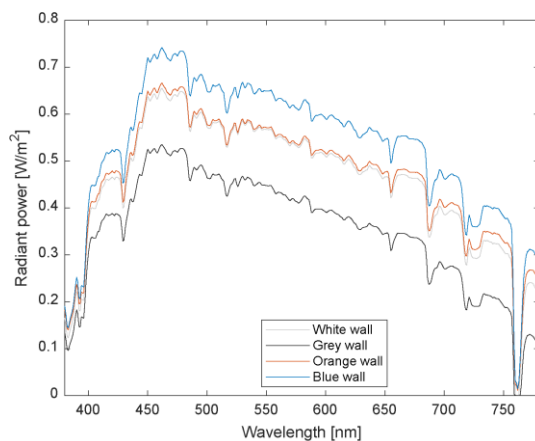| Wall colour	E_{Eh} [lx]	E_{Iv} [lx]	E_{Ih}[lx]	E_{Iv}/E_{Ih}	E_{Iv}/E_{Eh}	E_M [eml]	E_M/E_{Iv}
White wall	45730.0	1444.0	1446.6	1.00	0.032	1308.7	0.906
Grey wall	37690.0	1009.0	1116.6	0.90	0.027	990.3	0.982
Orange wall	46430.0	1080.0	1207.9	0.89	0.023	863.7	0.800
Blue wall	52800.0	1174.6	1286.5	0.91	0.022	1257.7	1.071

Figure 4. Spectral composition of total exterior daylight (S1 test point) during the second cycle experiment.
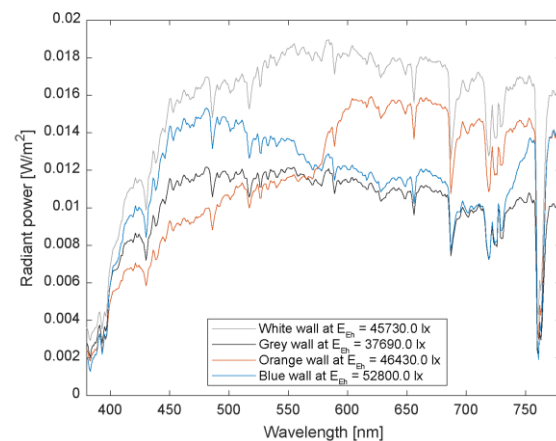
Figure 5. Internal spectral light composition at L3 test point   during the second cycle experiment. Note that each measurement was taken at different E_{Eh} (i.e. different time instants), refer to Figure 4.

3.3. Simulations

The performed simulations were divided into three stages. The first stage included the initial calibration of the virtual model in order to match the results obtained during the experiments. The other two stages encompassed the evaluation of indoor luminous conditions of the test cell under selected two dates representing extreme conditions of the year for the location of Ljubljana. During these two stages, the impact of different glazing types and interior finish spectral reflectivity on the indoor illuminance and circadian stimulus was investigated for the hours between 8:00 am and 12:00 pm. For the purpose of

identifying the relevant test days with appropriate climate conditions, a quick weather data analysis was carried out. The objective was to identify two days when the combination between the lowest daylight availability and the highest sky cover, as well as the highest daylight availability and the lowest sky cover were achieved.

3.3.1. Calibration procedure. The comparison between the simulated results acquired by the calibrated model and experiments is presented in Table 4. The results demonstrate that a high accuracy of the simulation model was achieved. The difference between the simulated and the measured E_{eh} values amounts only to 0.32 % with a similar difference of 3.75 % for the E_{Iv}/E_{Ih} ratio. These results confirm that the luminous sky distribution and indoor visual luminous environment were properly simulated by the virtual model. For the non-visual part of the simulations, the comparison between the calculated and the measured values resulted in extremely small differences of 0.0006 % for the E_M and 0.008 % for the E_M/E_{Iv} ratio. Therefore, it can be concluded that the developed virtual model faithfully reflects the real conditions and can therefore be used for further work.

Table 4. Experimental and simulated values of the calibration procedure with white internal wall finishes and view facing towards the window (30th of January 2019, 10:35 am).

	Glazing type	**E_{eh}[lx]**	**E_{Iv}[lx]**	**E_{Ih}[lx]**	**E_{Iv}/E_{ih}**	**E_{Iv}/E_{Eh}**	**E_M [eml]**	**E_M/E_{Iv}**
Experiment	triple pane low-e	25487.5	1099.4	549.1	2.00	0.043	999.8	0.909
Simulation	triple pane low-e	25405.2	1092.0	526.2	2.08	0.043	1000.4	0.916

3.3.2. Climate analysis. Using the weather data file for Ljubljana [25], the global horizontal illuminance and sky cover throughout the year were analysed and the day ranges for both daylight availability and scarcity were identified according to the global horizontal illuminance and sky cover values. The outcome of the performed climate analysis identified as the most suitable dates the 21st of July (i.e. best conditions) and the 21st of November (i.e. worst conditions). The data, provided by the utilised weather file, for the E_{Ih} and sky cover for the morning hours of 8:00 am to 12:00 pm are presented in Table 5. It can be concluded that for the 21st of July an intermediate sky type would be suitable for the simulations, while for the 21st of November an overcast sky would be appropriate.

Table 5. Weather file data for global horizontal illuminance and sky cover for the selected days for the simulation analysis (21st of July and 21st of November, 8:00 am to 12:00 pm).

	21st of July		**21st of November**	
Hour	**E_{Ih}[lx]**	**Sky cover[%]**	**E_{Ih}[lx]**	**Sky cover[%]**
8:00	60700	10	2700	100
9:00	76000	10	6000	100
10:00	90800	10	8600	100
11:00	96700	0	9900	100
12:00	99500	0	9600	100

3.3.3. Effect of glazing optical properties on the circadian stimulus. Glazing optical properties decisively impact the quality (i.e. spectral composition) and quantity (i.e. intensity) of daylight entering internal environments. Therefore, it is important to not only consider τ_{vis} as a single value calculated over the whole visible spectrum but to investigate the impact of spectral transmissivity of the glazing, because it could be selective only at certain wavelengths. This might be exceedingly important in the case of potential adverse impacts of glazing on the circadian stimulus of daylight in indoor environments. In this context, it is of interest to evaluate the impact of individual glazing technologies on the achieved light availability and light quality.

The simulated results of glazing type impact on the achieved indoor visual and non-visual daylighting confirm the findings of the experiments presented in section 3.1. From Figures 6 and 7 it can be clearly

seen that the differences between the achieved E_{Iv} and E_M are relatively small, with achieved ratios of E_M to E_{Iv} consistently close to or above 1.00 (maximum difference ~2 %), depending on the type of glazing, hour of day and sky conditions. As in the case of the experimental results, the only exception to the above described trend is the triple pane low-e glazing, which consistently exhibits the lowest vales of the achieved E_{Iv} and E_M (Figure 6 and 7) with the E_M/E_{Iv} ratio below 1.00 at all times. However, the absolute illuminance values achieved under different glazing types vary significantly. For instance, on the 21st of November at noon, the use of double pane low-e glazing results in $E_M = 878.0$ eml, but when a triple pane low-e glazing is used, the achieved circadian stimulus drops by ~37 % ($E_M = 554.9$ eml). The same reduction occurs during the analysed summer day; the only difference is that the effect would be less significant, because the excess of light would still allow the occupants to obtain appropriate circadian stimulus. Meanwhile, changing from a double pane to a triple pane low-e glazing, generates a reduction of ~39 % in the E_M values, while switching from double pane to double pane with low-e coating glazing results only in ~2 % variance. In general, the results of the simulations demonstrated that for the investigated glazing types the achieved circadian potential expressed through E_M under generic sky conditions is more or less proportional to the difference of the overall τ_{vis} of the studied glazing types.
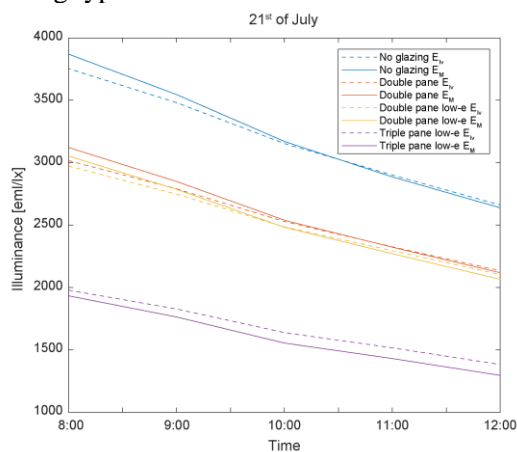

Figure 6. Simulated values of E_M and E_{Iv} at L3 test point facing the window, between 8:00 am and 12:00 pm on 21st of July in relation to different glazing types.
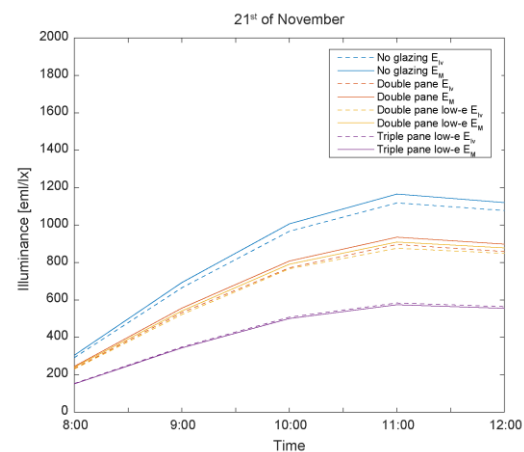
Figure 7. Simulated values of E_M and E_{Iv} at L3 test point facing the window, between 8:00 am and 12:00 pm on 21st of November in relation to different glazing types.

3.3.4. Effect of interior finish optical properties on the circadian stimulus. As mentioned above, the internal daylight distribution is also governed by the light reflections from the internal room surfaces. Therefore, the spectral composition of the reflected light (i.e. spectral reflectivity) will influence the resulting circadian potential of the indoor environment. The importance and potential substantial impact of the colour of internal surfaces was exposed through the experimental results (see section 3.2) in the case of the orange (negative influence) and blue (positive influence) wall finishes. Therefore, the main objective of the executed simulations was to investigate the relation between relative impact of the investigated specific colours and generic sky conditions. In the case of experiments, the glazing properties for the simulations were fixed at double pane glazing without low-e coating.

    The simulated results for the 21st of November and 21st of July presented in Figures 8 and 9, respectively, go along with the results found for the validation procedure (i.e. small differences between E_M and E_{Iv} for winter conditions), and demonstrate that the largest impact of wall colour on the resulting circadian potential in the analysed model is achieved in the case of the orange wall, when compared to the spectrally neutral white wall. For instance, under the same daylighting conditions and fixed glazing type properties, variation in the resulting E_M values between the white and orange wall are in the range of ~15-16 % (e.g. 21st of July at 12:00 pm: E_M for white wall = 969.9 eml, E_M for orange wall = 817.1 eml). For other colours, the change of the simulated E_M values are less pronounced, with variance

between white and grey at ~6-10 % and white and blue at ~10-16 %. However, it has to be stressed that a white coloured wall has a higher R_{vis} value than the rest of the analysed colours (Table 1). This means that at least part of the variance in the resulting E_M values presented in Figures 8 and 9 is the result of change in the R_{vis} value of the wall. Therefore, the impact of different spectral reflectivity of wall finishes on the ensuing circadian potential of the model is best observed by comparing the results for grey (R_{vis} = 0.54) orange (R_{vis} = 0.56) and blue (R_{vis} = 0.59) colours that have comparable R_{vis} values. In this context, the change from a blue wall finish to an orange one results in the reduction of E_M value by ~10 %, while switching from grey to orange wall colour would result in ~6 % reduction of the E_M value.
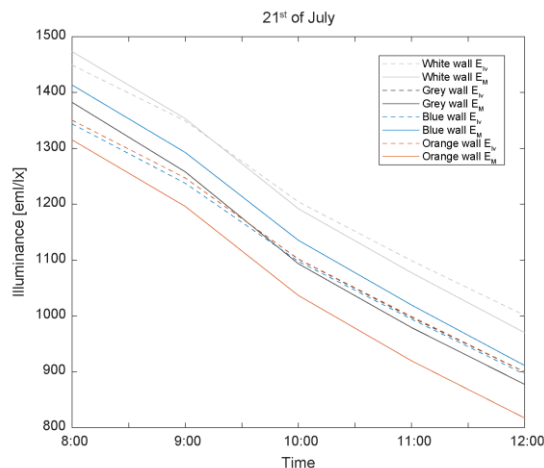

Figure 8. Simulated values of E_M and E_{Iv} at L3 test point facing the wall, between 8:00 am and 12:00 pm on 21st of July in relation to different wall finishes.
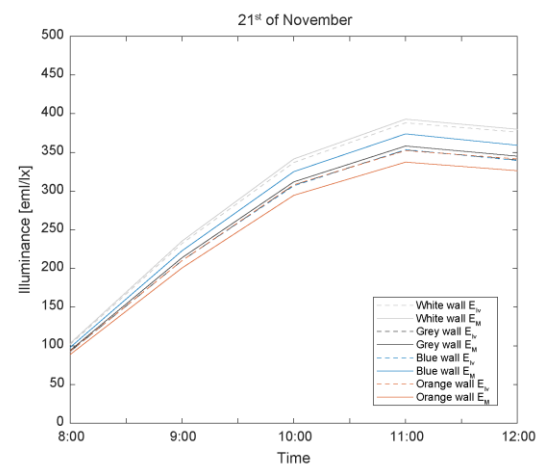

Figure 9. Simulated values of E_M and E_{Iv} at L3 test point facing the wall, between 8:00 am and 12:00 pm on 21st of November in relation to different glazing types.

4. Discussion and conclusions

The main objective of the presented analysis was to investigate the relative impact of selected glazing types and wall colours on the ensuing circadian potential as well as achieved indoor illuminance of a daylit room. The subject was approached through experiments conducted on a scale model setup, as well as simulations executed on a virtual model calibrated using experimentally derived data and later used for calculations under generic environmental conditions (i.e. CIE sky types and CIE D65 illuminant). The obtained results are directly relatable to a small cellular office with a window to wall ratio of 16 % and north orientation, located at Ljubljana, but can also be generalized to some degree to other situations, locations and configurations. Furthermore, results could guide designers to select a proper combination of glazing technologies and interior finish types, which could enhance the utility, productivity and/or convenience of the room for specific activities (e.g. recovering patients in a hospital requiring certain light spectrum content).

Based on the acquired experimental and simulation results, it can be concluded that for the analysed spectrally neutral glazing types the resulting impact on the achieved circadian potential of the indoor environment, measured in the equivalent melanopic lux, is more or less proportional to τ_{vis} of a specific type of glazing. However, both experiments and simulations using generic environmental conditions have exposed a considerable negative impact on the circadian potential in the case of the triple glazed low-e glazing. For instance, double pane, double pane low-e and triple pane low-e glazing displayed E_{Ih} within the recommended ranges during 21st of July however, for 21st of November triple pane low-e fails to deliver enough daylighting between 8:00 and 9:00 am, with concurrent lowest E_M values (E_M = 151 lx), which is potentially harmful during this period of the year in which the daylight availability is reduced by intensity and duration throughout the day. In this case the application of two low-e films affects the spectral transmissivity at shorter wavelengths to such degree that under all investigated external conditions the indoor melanopic illuminance (E_M) recorded at the position of a hypothetic occupant's eye is consistently lower than vertical illuminance (E_{Iv}). Based on these results,

although in the case of the spectrally neutral glazing types the resulting E_M is conditioned by τ_{vis} of glazing, this is most probably not true for glazing types that non-uniformly affect the spectral composition of daylight (e.g. solar protective glazing, coloured glazing, coloured embedded shading, etc.). The second part of the executed study investigated the impact of different spectral reflectivity of wall coverings on the indoor luminous conditions in the case of a hypothetical occupant facing the coloured wall with a window to the side (i.e. daylight entering from the left). The results demonstrated a substantial influence of colour on the achieved circadian potential of the scale model. In particular, it can be deduced from the results that blue colour hues can have a positive impact on the achieved level of E_M when compared to spectrally neutral colour at comparable R_{vis}. On the contrary, the orange tones have a distinct negative impact, considerably reducing E_M values when compared to E_{Iv} as well as E_M achieved under spectrally neutral wall finish. The obtained results of the relative impact of wall finish spectral reflectivity on the achieved circadian potential of the indoor environment is in line with the findings reported by Cai et al. [15].

Based on the reported findings of the presented study it could be concluded that colour of internal surfaces has a greater impact on the achieved circadian potential in the indoor environments than does the glazing type. Nonetheless, it should be stressed that the direction of occupant's view can potentially significantly influence the resulting final circadian impact. In other words, if the hypothetical occupant presumed in the present analysis did not face directly towards the coloured wall, but rather towards the window, the resulting impact would be far smaller or even marginal. On the other hand, if the glazing type was not spectrally neutral, as it was in the case of the conducted experiments and simulations, its relative impact could be greater. Both above exposed notions point towards the need for further research that would enlighten the range of impacts exerted by various spectrally neutral and spectrally selective glazing types as well as wider range of wall colours, and combinations, on the achieved circadian potential of daylight in indoor environments. Concurrently, also the impact of occupant view direction and the interactions between glazing type, shading systems, and wall colour need to be considered, as they might have a decisive impact when dealing with the circadian aspects exerted by the built environment.

Acknowledgments

References

[1]   Quintero JE, Kuhlman SJ and McMahon DG 2003 The biological clock nucleus: a multiphasic oscillator network regulated by light. *J Neurosci* 23:8070–6.

[2]   Zhang SL and Sehgal A 2019 *11 - Circadian Rhythms and Disease. In: Pyeritz RE, Korf BR, Grody WW, editors. Emery and Rimoin's Principles and Practice of Medical Genetics and Genomics (Seventh Edition), Academic Press* 299–314. Available at: doi:10.1016/B978-0-12-812536-6.00011-0.

[3]   Weissová K, Škrabalová J, Skálová K, Červená K, Bendová Z, Miletínová E, et al. 2018 Circadian rhythms of melatonin and peripheral clock gene expression in idiopathic REM sleep behavior disorder *Sleep Medicine* 52:1–6. Available at: doi:10.1016/j.sleep..07.019.

[4]   Chellappa SL, Steiner R, Blattner P, Oelhafen P, Götz T and Cajochen C 2011 Non-Visual Effects of Light on Melatonin, Alertness and Cognitive Performance: Can Blue-Enriched Light Keep Us Alert? *PLOS ONE* 6:e16429. Available at: doi:10.1371/journal.pone.0016429.

[5]   Figueiro MG, Steverson B, Heerwagen J, Kampschroer K, Hunter CM, Gonzales K, et al. 2017 The impact of daytime light exposures on sleep and mood in office workers *Sleep Health* 3:204–15. Available at: doi:10.1016/j.sleh.2017.03.005.

[6]   Viola AU, James LM, Schlangen LJ and Dijk D-J 2008 Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality *Scandinavian Journal of Work, Environment & Health* 34:297–306. Available at: doi:10.5271/sjweh.1268.

[7]   Provencio I, Rodriguez IR, Jiang G, Hayes WP, Moreira EF and Rollag MD 2000 A novel human opsin in the inner retina *J Neurosci* 20:600–5.

[8]   Brainard GC, Hanifin JP, Greeson JM, Byrne B, Glickman G, Gerner E, et al. 2001 Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor *J Neurosci* 21:6405–12.

[9]   Thapan K, Arendt J and Skene DJ 2001 An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans *J Physiol* 535:261–7.

[10]   Kozakov R, Franke S and Schöpp H 2008 Approach to an Effective Biological Spectrum of a Light Source *LEUKOS* 4:255–63. Available at: doi:10.1582/LEUKOS.2008.04.04.004.

[11]   Rea M, Figueiro M, Bierman A and Hamner R 2012 Modelling the spectral sensitivity of the human circadian system *Lighting Research & Technology* 44:386–96. Available at: doi:10.1177/1477153511430474.

[12]   Lucas RJ, Peirson SN, Berson DM, Brown TM, Cooper HM, Czeisler CA, et al. 2014 Measuring and using light in the melanopsin age *Trends in Neurosciences* 37:1–9. Available at: doi:10.1016/j.tins.2013.10.004.

[13]   Woelders T, Beersma DGM, Gordijn MCM, Hut RA and Wams EJ 2017 Daily Light Exposure Patterns Reveal Phase and Period of the Human Circadian Clock *J Biol Rhythms* 32:274–86. Available at: doi:10.1177/0748730417696787.

[14]   Konis K 2018 Field evaluation of the circadian stimulus potential of daylit and non-daylit spaces in dementia care facilities *Building and Environment* 135:112–23. Available at: doi:10.1016/j.buildenv.2018.03.007.

[15]   Cai W, Yue J, Dai Q, Hao L, Lin Y, Shi W, et al. 2018 The impact of room surface reflectance on corneal illuminance and rule-of-thumb equations for circadian lighting design *Building and Environment* 141:288–97. Available at: doi:10.1016/j.buildenv.2018.05.056.

[16]   Inanici M, Brennan M and Clark E 2015 Spectral Daylighting Simulations: Computing Circadian Light *vol. 2015, Hyderabad: International Building Performance Simulation Association* 1103–9.

[17]   Hraška J, Hanuliak P, Hartman P, Zeman M and Stebelová K 2014 Comparative Study of Window Glazing Systems Influence on Melatonin Secretion in Patients in the Hospital Wards *Advanced Materials Research*. Available at: doi:10.4028/www.scientific.net/AMR.899.288.

[18]   Ewing PH, Haymaker J and Edelstein EA 2017 Simulating Circadian Light: Multi-Dimensional Illuminance Analysis. *vol. 2017, San Francisco, CA: International Building Performance Simulation Association* 2363–71. Available at: doi: https://doi.org/10.26868/25222708-2017.660.

[19]   Sadeghipour Roudsari Mostapha, Pak M and Smith A 2013 Ladybug: A parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design *Proceedings of BS 2013, Chambéry: International Building Performance Simulation Association*.

[20]   Lucas RJ, Peirson SN, Berson DM, Brown T, Cooper H, O'Hagan JB, et al. 2013 *Irradiance Toolbox. Oxford*.

[21]   Ahlborn 2019 The ALMEMO system. [Online] available: https://www.ahlborn.com/en_UK/almemo (accessed February 11, 2019).

[22]   BLACK-Comet UV-VIS Spectrometer. StellarNet Inc 2019. [Online] available at: https://www.stellarnet.us/spectrometers/black-comet-uv-vis-concave-grating-spectrometers/ [accessed February 11, 2019]

[23]   Inanici M and Liu Y 2016 Robust Sky Modelling Practices in Daylighting Simulations *PLEA 2016, Los Angeles* 679–85.

[24]   ARSO Slovenian Environment Agency 2019. [Online] available at: http://www.meteo.si/ [accessed March 8, 2017]

[25]   EnergyPlus Weather Data 2019. [Online] available at: https://energyplus.net/weather [accessed March 2, 2018]

[26]   Ward Larson G and Rob AS 2004 *Rendering with Radiance The Art and Science of Lighting Visualization*.