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Assessing Photopic and Melanopic Daylighting Performance of Special Glazing System: A Full-scale Experiments

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Abstract

Comparative research on the influence of daylight and visual environment on melatonin oscillations and the performance of space users was realized in two identical rooms with different glazing at the Faculty of Civil Engineering of the Slovak Technical University in Bratislava. The glazing in the windows had significantly different transmittances of melanopic light. This article presents measured changes in the intensity of photopic and melanopic daylighting values inside the rooms on horizontal and differently oriented vertical plane. Photopic and melanopic illuminances were measured under cloudy and partly clear skies during several months in 2021 and 2022. The article is also partially devoted to the effect of light from a computer monitor on the spectral composition of light on the eye of a person working with a computer. The article also analyzes the problems associated with the evaluation of non-visual aspects of daylighting of the interior spaces of buildings.

Keywords: daylighting, melanopic light, glazing, illuminance, health

1 Introduction

When designing the daylighting of buildings, attention is primarily paid to the amount of photopic light in the interiors, which depends mainly on the photopic transmittance of the glazing and the size of the glazing. If we work with spectrally neutral glazing and spectrally neutral internal and external surfaces, the above approach is understandable. Currently, there are many glazing and shading devices on the construction market, which significantly change the spectral composition of daylight [1]. This may have an impact on the non-visual effects of light, which are strongly associated with the light regulation of the circadian biological clock [2–4]. Non-visual photoreception is essentially associated with the intrinsically photosensitive retinal ganglion cells that contain the photoreceptor melanopsin. In [5], the sensitivity of melanopsin to light was standardized, and the terms "melanopic illuminance" or "melanopic light" are gradually becoming established in the literature. According to [6] "...our data demonstrate the widespread utility of melanopic illuminance as a metric for predicting the circadian impact of environmental illumination". If there is little light in the indoor environment of buildings and it has an inappropriate spectral composition, hormonal processes in the human

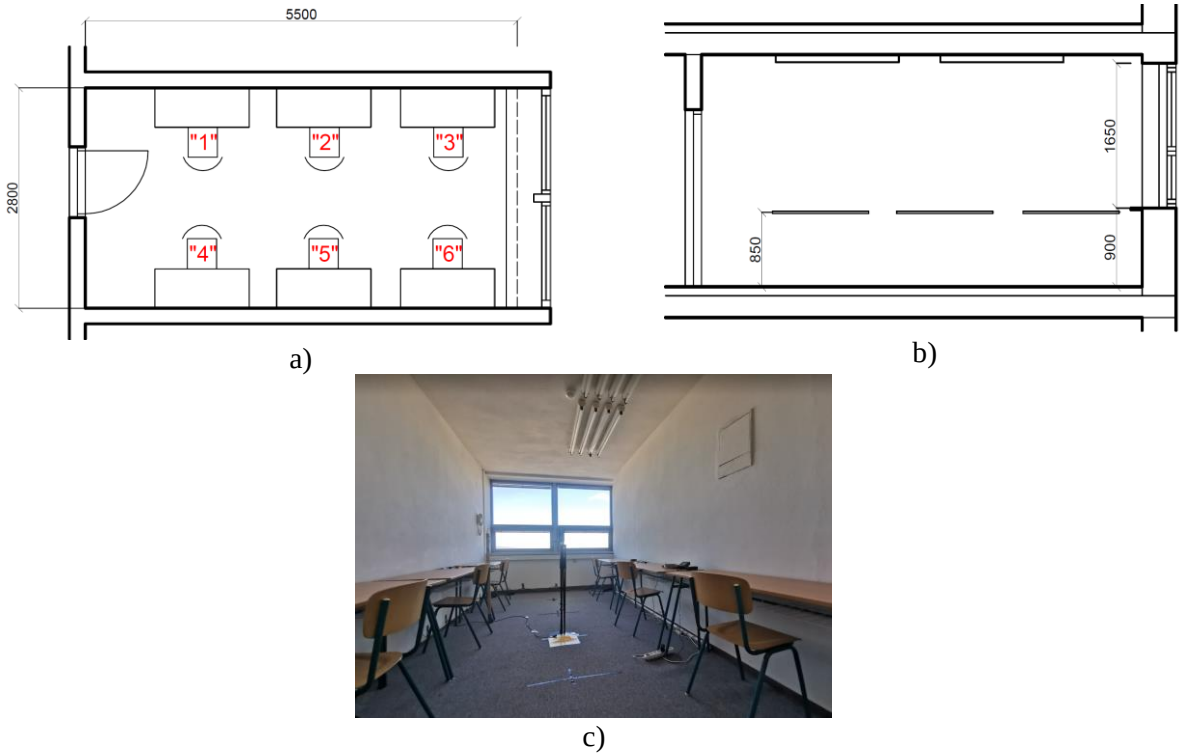
body (e.g., melatonin, cortisol, serotonin) are disrupted, which affects both physiological and mental health. Health disorders are manifested in changes in the temperature of the human body, fatigue, depression, problems with natural sleep cycles, heart disease, obesity and even some types of cancer [7–8].
Prevention of the mentioned problems is enough intense and dynamic daylight that enters the eyes. In localities where cloudy skies dominate, it is important to ensure enough daylight in the interior of buildings, especially when the sky is overcast. Non-visual effects depend on the intensity, duration, timing, spectral composition, directionality and history of light entering a person's eyes. Circadian light is usually quantified in practice by the levels of melanopic illuminance on vertical planes, usually at a height of 1.2 m above the floor of the room, which represents the height level of the eyes of a seated person. The evaluation of vertical illuminance within climate-based daylight modeling, which uses annual daylight performance metrics, represents a radical change in the way of evaluating the indoor light environment. Various computer simulations of the illumination of the eyes of the building's users are rarely verified by measurements [8–10]. The high dynamic of natural light, variations in brightness and spectrum of the internal light environment, movement of users in space and changes in view directions basically do not even allow verification of annual simulation calculations.
This article presents part of the measured data on the photopic and melanopic light conditions in two identical and adjacent rooms, in which research was conducted in the winter months of 2021 and 2022 on the influence of different daylight on the oscillations of melatonin in the bodies of the experiment participants and also on their work performance and sleep quality. From the point of view of the goals of the experiment, very different optical properties of the glazing in the rooms were chosen. Here we present some measured data on the lighting environment in rooms only in relatively stable conditions of the outdoor daylight climate. In this study, we also marginally address the issue of circadian (melanopic) illuminance metrics.

2 Methodology

In this paper, the authors realized a full-scale experimental study to investigate horizontal and vertical daylight illuminance in two rooms with identical geometries and different glazing in conditions of cloudy and partly clear skies in Bratislava. In overcast sky conditions, horizontal and vertical illuminance was measured in several places in a room with glazing that significantly reduces the transmittance of the blue component of light (tested room). Horizontal illuminance was measured at a height of 0.85 m above the floor and vertical illuminance at a height of 1.2 m. The lighting of the occupant's eyes while working on a laptop at several computer workstations in the room was also measured. In the conditions of mostly clear days, the daily photopic light was continuously measured on the outer surface of the window and in the middle of the depth of both rooms and their longitudinal axis. The sensor measuring photopic and melanopic light was at a height of 1.2 m above the floor and was oriented perpendicular to the window. Illumination was taken at intervals of several tens of seconds.
At the time of measurements, the sun did not shine directly into the rooms. Blinds were not used during all measurements. During the presented measurements in clear sky conditions, there were 6 occupants in the room who worked with notebooks.

2.1 Rooms Description

The measured rooms are located on the 21st floor of the Faculty of Civil Engineering of the Slovak University of Technology in Bratislava, Slovakia. The basic geometric dimensions of the room are shown in Figure 1. The clear height of the rooms is 2.67 m. The windows of the rooms are oriented to the north-east (the deviation of the normal of the windows from the north is 29°). The window in each room is 2.8 m wide, 1.65 m high, and its lower profile is 0.90 m above the floor. The window frames are made of aluminium and have a light gray color. Buildings or terrain orography practically does not at all shade the windows of the rooms. The building surfaces of the room are spectrally neutral. The walls and ceiling are white, the carpet on the floor is dark gray, and the window frames are light gray. The coating of the walls and ceiling has a photopic light reflectance value of 0.75 and melanopic light reflectance is about 0.74. Carpet and window frames have the same photopic and melanopic light reflectance, with carpet 0.32 and window frames 0.49. There was a minimum of furniture in the room, the surfaces of which had an ocher color. A room with a standard triple-glazed window is called the "reference room" within the experiment. A room with a window with special glazing is called a "tested room".
Measurements were made on the axis of the room and at the working positions numbered in Figure 1.



a) b)

c)

Figure 1: The room where the measurements were taken
a) floor plan of the office with marked workplaces, b) longitudinal section of the office, c) view of the office in the state of preparation of measurements

2.2 Main Measuring Devices

The new MSC 15 light spectrum meter from Gigahertz-Optik GmbH (Figure 2a) was used for the measurement of the photopic and melanopic illuminance and other spectral characteristics of light. MSC15 covers a spectral range between 360 nm and 830 nm with a spectral bandwidth of 10 nm and soffers a wide measurement range for illuminance and color between 1 lx and 350,000 lx. The device can be operated manually, or measured data can also be stored in a computer running Windows as GOS extension source files, which are exported in ASCII and ExcelTM formats. This device was used in experiments to measure melanopic and photopic parameters, especially in measurements under overcast sky conditions.
The compact illuminance spectrophotometer CL-500A (Figure 2b) can measure illuminance, color temperature, color rendering index, chromaticity, and spectral power distribution. The spectral irradiance is measured at 1 nm pitch from 360 to 780 nm. The measuring range is from 0.1 to 100.000 lx, with accuracy for illuminance ±2%. The data management software CL-s10w is included as a standard accessory. These devices were located in the center of the rooms at a height of 1.20 m over the floor and were oriented toward the window.
The probe for measuring illuminance FLA 623 VL (Figure 2c) has spectral sensitivity from 380 to 720 nm and a measuring range from 0 to 170.000 lx. The absolute error of measured data is less than 5%. This photometer was placed on the outside of the window frame in a vertical position and in short time intervals, the intensities of the photopic illumination of the window were recorded by the computer.
The CM-5 spectrophotometer (Figure 2d) makes it possible to measure the spectral reflectance of opaque materials or the transmittance of transparent samples, including liquid ones, in the wavelength range of 360 to 740 nm with a pitch of 10 nm. The photopic light transmittance and reflectance of room materials were measured with this device.
Melanopic (circadian) parameters were measured in accordance with the CIE S 026/E:2018 [5].



a) b) c) d)

Figure 2: The main devices used in the measurements
a) Gigahertz-Optik MSC15 spectral light meter, b) Konica Minolta illuminance color meter CL 500A, c) Ahlborn Almeno FLA 623 VL radiation probe for measuring illuminance, d) Konica Minolta spectrophotometer CM-5

2.3 Photopic and Melanopic Properties of the Windows

In the tested room, Orange 50 UV foil [11] was added to the window glazing. The spectral light transmittance of this foil is in Figure 3. The photopic light transmittance of the foil Orange 50 UV is 0.51 and melanopic light transmittance of the foil is 0.11.

The clear triple glazing in the reference room has a visible light transmittance of 0.70 (diffuse photopic light transmittance is 0.64). The diffuse melanopic light transmittance of clear triple glazing is 0.67.
The triple glazing with added foil Orange 50 UV in the tested room has a diffuse photopic light transmittance value of 0.39 and diffuse melanopic light transmittance is 0.10. Typical spectral irradiance leaving clear triple glazing under an overcast sky and spectral irradiance leaving triple glazing supplemented with foil Orange 50 UV are shown in Figure 4.

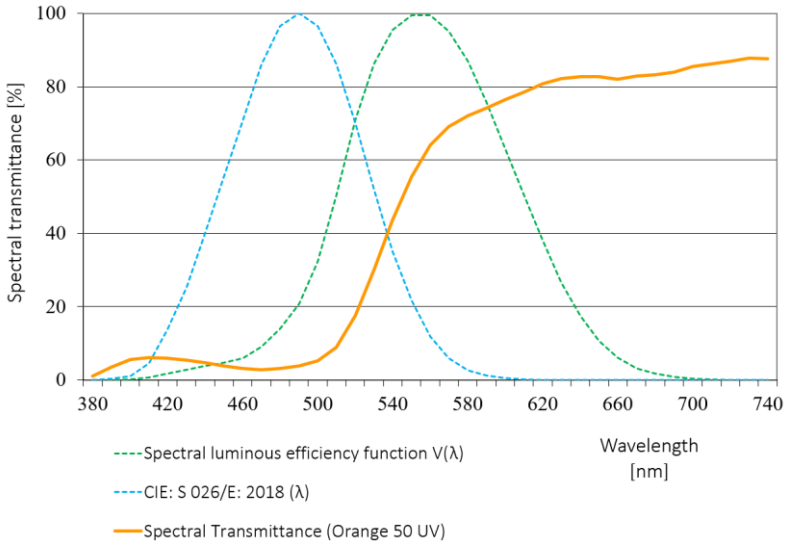


Figure 3: Spectral light transmittance of the foil Orange 50 UV and the CIE photopic and melanopic functions

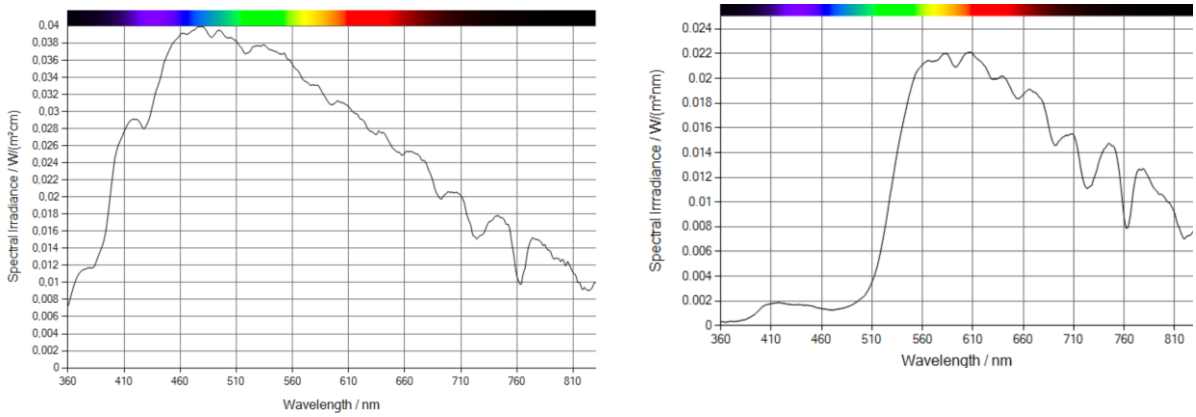


Figure 4: Typical spectral irradiance leaving clear triple glazing at the time of measurement under the overcast sky (left – ratio $E_{vp} / E_{vm} = 1.01$) and spectral irradiance leaving triple glazing supplemented with foil Orange 50 UV (right – ratio $E_{vp} / E_{vm} = 4.18$)

3 Results and Discussion

Only a small part was selected from the measured data on the light environment in the reference and tested room. However, the presented data provide a sufficient idea of how problematic it is

to evaluate photopic and melanopic light that reaches the eyes of users of building interiors, even in relatively stable conditions of the outdoor daylight climate. We have divided the analysis of the results into three sections - a part of the measured data under an overcast sky in an unoccupied tested room, a part under conditions of predominantly clear sky when people were working in the rooms, and a part in which we compare the measured data with current circadian metrics, especially melanopic illuminance.

3.1 Daylighting of the Tested Room under the Overcast Sky

The measurement results presented here are from the morning hours of a cloudy day on November 3, 2021. In the morning around 9:00 a.m., it was foggy. Then it was evenly cloudy until about 11:00 a.m. when very thick to black clouds arrived. Subsequently, the state of the sky returned to a uniformly cloudy sky, and around noon, the vertical illuminance of the window reached a level of illuminance similar to what it was at approximately 10:30 a.m. The illumination levels of the window of the tested room during the measurements are shown in Figure 5.

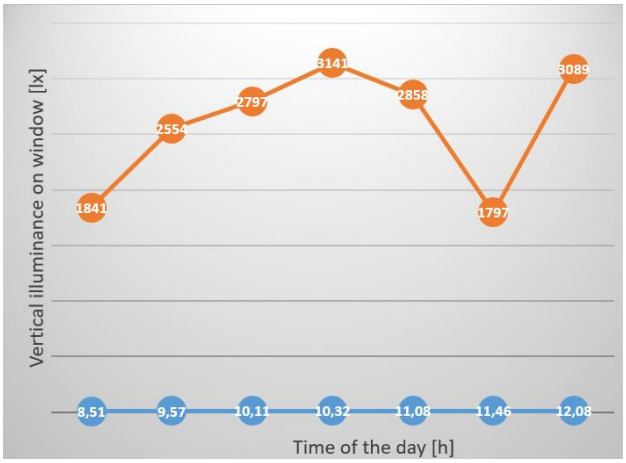
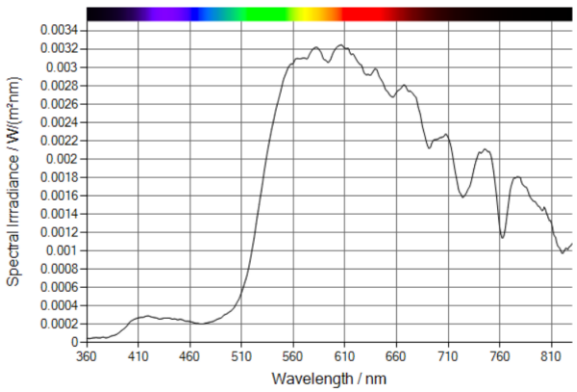


Figure 5: Vertical photopic illuminance of the window during measurements on November 3, 2021

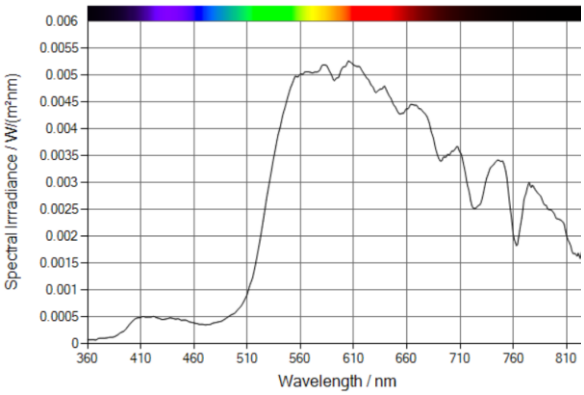
Table 1: Photopic and melanopic illuminance in the axis of the tested room in a place 2.3 m and 4.1 m from the window – 11/3/2021

Measured location / direction of view	**Time [h]**	**Illuminance 2.3 m from the window [lx]**		**Time [h]**	**Illuminance 4.1 m from the window [lx]**	
		Photopic	Melanopic		Photopic	Melanopic
Horizontal 0.85 m above the floor	10:15	175.5	43.5	10:53	62.4	15.5
Vertical 1.2 m above the floor / view towards the window	10:20	287.0	73.4	10:56	107.3	27.3
Vertical 1.2 m above the floor / view towards the side wall	10:22	72.5	17.3	10:58	39.5	9.6
Vertical 1.2 m above the floor / view towards the back wall	10:23	42.3	10.2	11:00	24.5	5.9

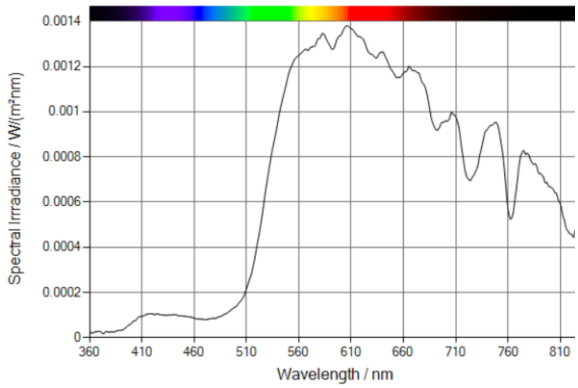
Horizontal and vertical photopic and melanopic illuminances in the axis of the tested room in a place 2.3 m and 4.1 m from the window are in Table 1. Table 1 also shows the times of recording the illuminances. Vertical illuminances in the direction of the window are significantly higher than horizontal illuminances in the same place. In the deeper parts of the room, vertical illuminances are almost twice as high as horizontal ones. The mutual ratios between the illuminances of different oriented vertical planes and the horizontal illuminance change significantly with the orientation of the vertical planes and with the depth of the measured location in the room.



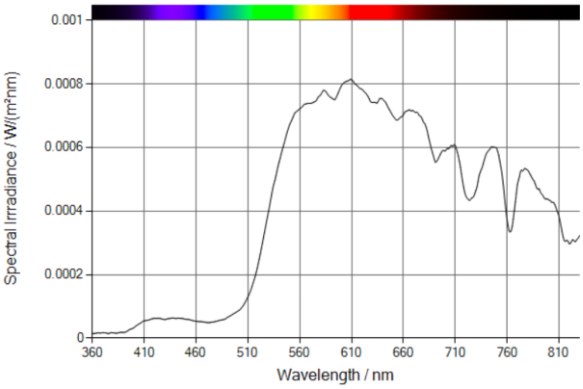
a) horizontal, 0.85 m above the floor



b) vertical towards the window, 1.20 m above the floor



c) vertical towards the side wall, 1.20 m above the floor



c) vertical towards the back wall, 1.20 m above the floor

Figure 6: Spectral irradiance levels of daylight received on horizontal and vertical surfaces in the axis of the tested room at a distance of 2.3 m from the window

Figure 6 documents that in an empty room with spectrally neutral surfaces, the spectral composition of light is the same and does not depend on the orientation of the vertical plane. Of course, the intensity of spectral irradiance changes significantly with a change in the orientation of the measured vertical plane.

Characteristic spectral irradiance of the eyes of a person working with a laptop at workplace no. 3 (see Figure 1) at a distance of 2 m from the window of the tested room is in Figure 7 (left). At workplace no. 3 the photopic illuminance on the eyes of a person working on a laptop at a distance from the screen around 0.5 m was E_{vf} = 67 lx and the melanopic illuminance was

E_{vm} = 23 lx, the ratio E_{vf} / E_{vm} is 2.9. Characteristic spectral irradiance of the eyes of a person working with a laptop at workplace no. 1 at a distance of 4 m from the window is in Figure 7 (right). At workplace no. 1 the photopic illuminance on the eyes of a person working on a laptop at a distance from the screen around 0.5 m was E_{vf} = 37 lx and the melanopic illuminance was $E_{,m}$ = 17 lx. The ratio of photopic and melanopic illuminance of the eyes is E_{vf} / E_{vm} = 2.2.
At a workplace 4 m away from a window, the total illuminance on the eyes of a person working on a computer will decrease. The light falling from the computer screen on the eyes at the workplace no. 1 is the same as at workplace no. 3. The intensity of daylight at workplace no. 1 is significantly lower than at workplace no. 3. The blue part of the screen's light spectrum will improve the ratio of photopic to melanopic illuminance in favor of melanopic illuminance.

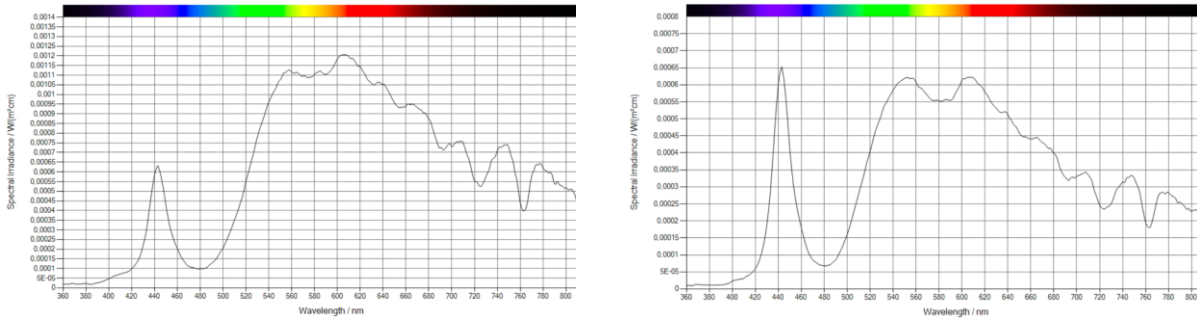


Figure 7: Characteristic spectral irradiance of the eyes of a person working with a laptop at workplace 3 (see Figure 1; left – ratio E_{vp} / E_{vm} = 2.9) and spectral irradiance of the eyes of a person working with a laptop at workplace 1 (right – ratio E_{vp} / E_{vm} = 2.2)

3.2 Daylighting of Both Rooms in Conditions of Partly Clear Sky

During the days from 1/18/2022 to 1/21/2022, in mostly clear sky conditions, several parameters of daylighting were continuously measured in both rooms. In this article, we only report the measured illuminances on the outer surface of the windows and the vertical illuminances in the center of the room towards the windows. At the time of measurements, 6 people were working on laptops in both rooms.
The vertical illuminances on the outer surface of the windows of the rooms are in Figure 8.

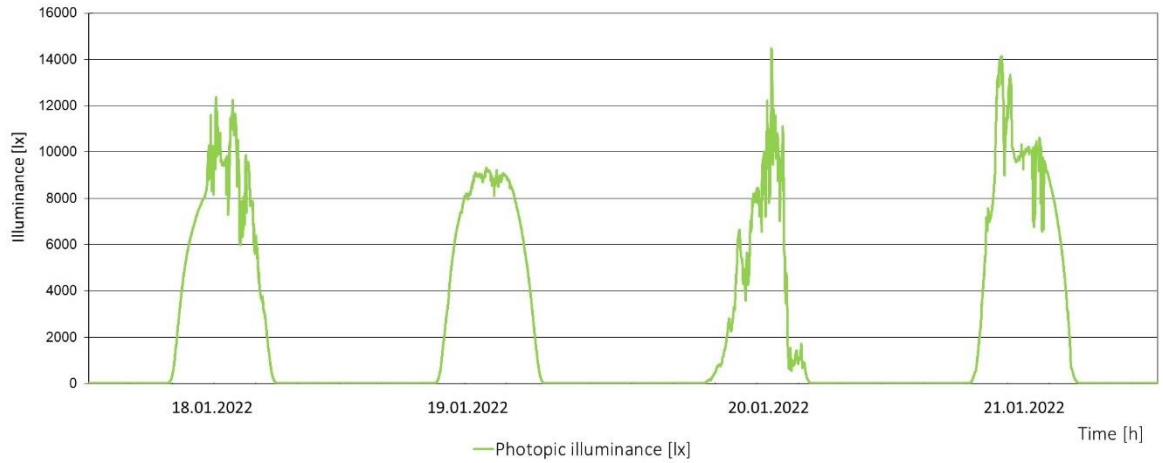


Figure 8: Vertical photopic illuminance on the external side of rooms windows

Figure 8 shows the sky lighting and the reflected light from the buildings and the terrain below the windows. Due to the relatively intense direct sunlight falling on the buildings and terrain, the reflected component of light has a significant share in the total illumination of the windows. Reflected light from buildings and terrain also has a slightly different spectral composition than a skylight.

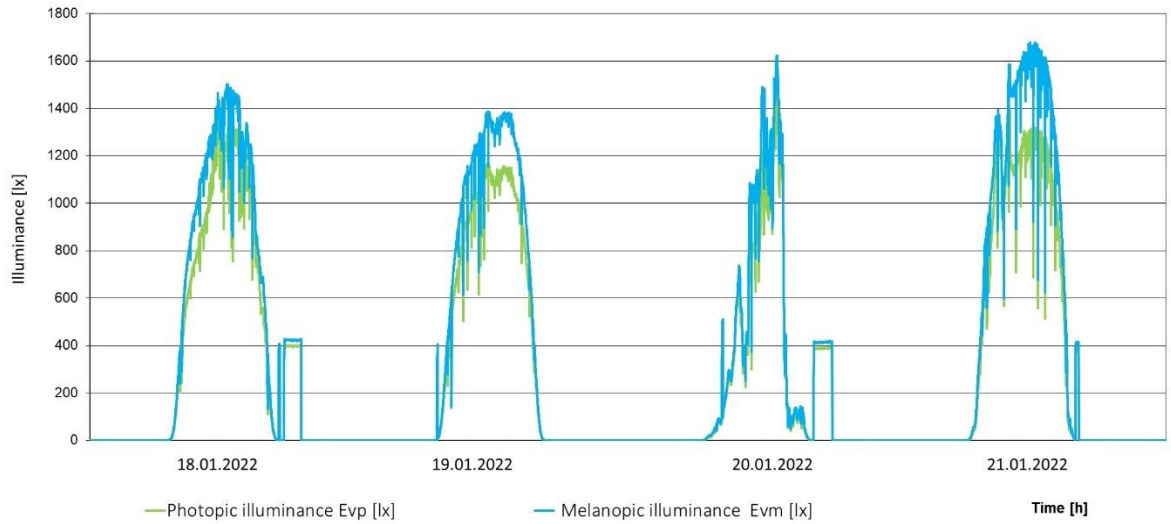


Figure 9: Photopic and melanopic illuminances of the vertical plane in the center of the reference room at a height of 1.2 m above the floor towards the window

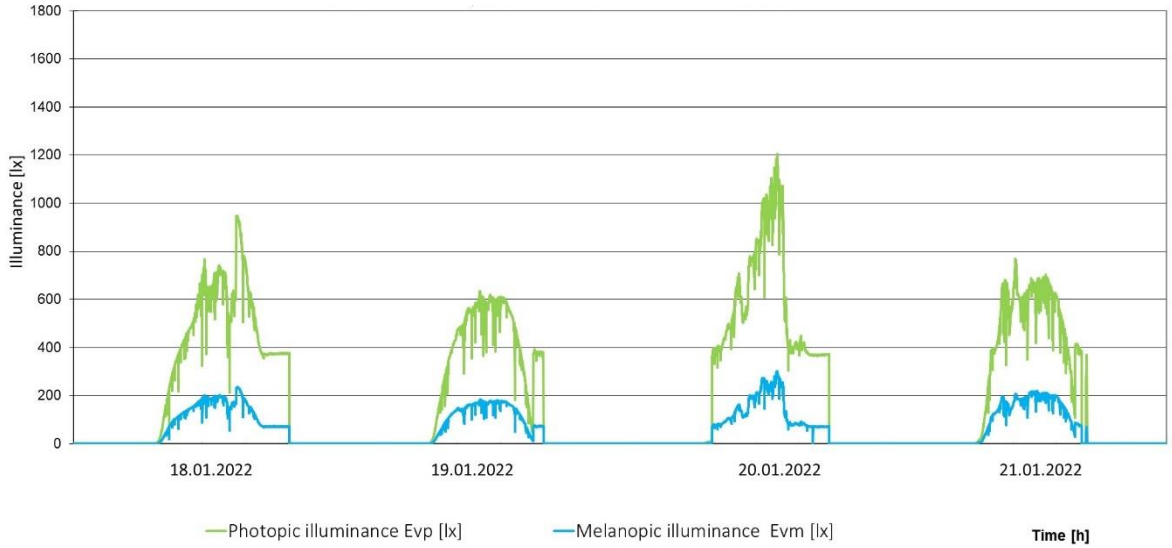


Figure 10: Photopic and melanopic illuminances of the vertical plane in the center of the tested room at a height of 1.2 m above the floor towards the window

Photopic and melanopic illuminance of a vertical plane in the center of the reference room at a height of 1.2 m above the floor towards the window is shown in Figure 9. Melanopic illuminance is higher than photopic for several reasons. The triple glazing in the window has a slightly higher transmittance of melanopic light than photopic light, and the share of blue light in the room also slightly increases the light from computer screens. However, the main reason for higher melanopic illuminance than photopic illuminance is that light from a clear sky contains more melanopic than photopic component. The rectangles in Figure 9 at the end of days 18 and 20 January 2022 are created by artificial lighting. At this time, at the end of daylight, instruments were checked under artificial lighting and other work was carried out that required experiments.

The difference between photopic and melanopic illumination in the tested room is significant due to the low transmittance of the blue component of the light spectrum - Figure 10. In the tested room, the blue component was not increased by the light from the computer screens, because for the purpose of the experiments, the computer screens were covered with a foil that does not transmit blue light.

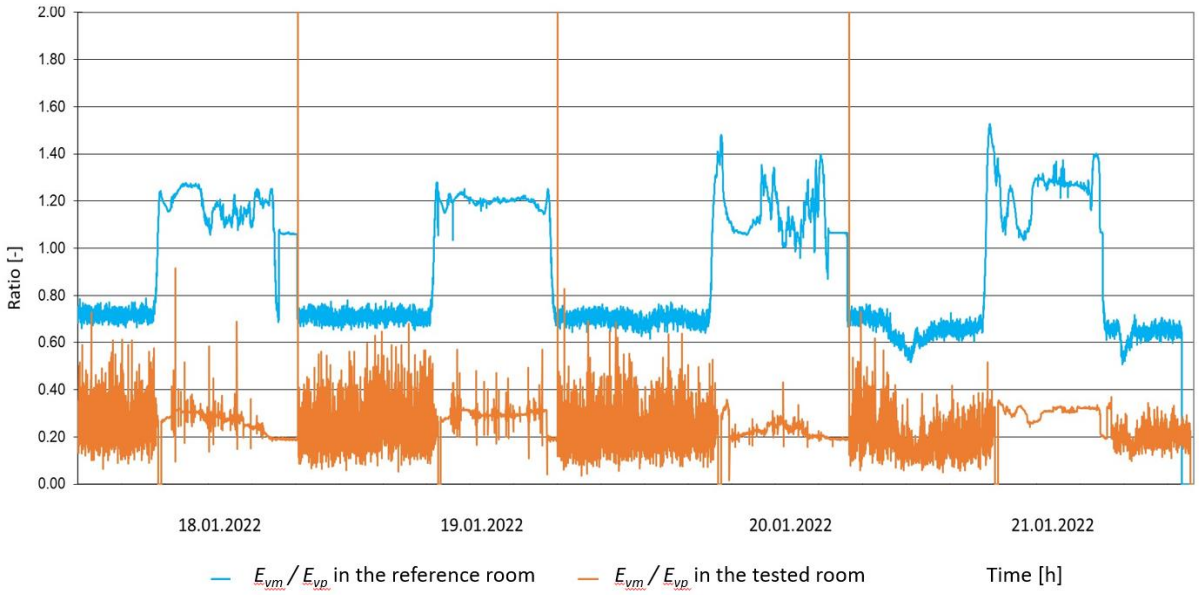


Figure 11: Ratio of melanopic illuminance to photopic illuminance in both measured rooms

Figure 11 shows that on clear days there is about 20% more melanopic light than photopic light in the center of the reference room at a height of 1.2 m above the floor towards the window. Conversely, in the tested room, the melanopic light level is only about 25% of the photopic light level. The measured rooms are located in the central part of Bratislava, where many light sources shine at night. The ratio of melanopic to photopic night light is approximately 0.70 in the reference room. The high oscillation of the melanopic to photopic night light ratio in the tested room is a consequence of the low light transmission through the windows and the light produced by the measuring devices in the room.

3.3 Performance Criteria for Non-Visual Light Evaluation

In the field of research into the non-visual effects of light, the greatest attention is paid to artificial light and its influence on the circadian stimulus. For artificial lighting, several methods and criteria for evaluating circadian (melanopic) lighting are recommended [for example in 12–14], but they differ from each other and are often fundamentally modified in short time intervals. Although these metrics are used to assess circadian aspects of daylighting, such a procedure cannot be considered correct. The reason for this statement is the high dynamics of the intensities and spectral composition of daylight. Despite the fact that assessing and evaluating melanopic daylighting is problematic, we will compare the measured illuminance in both rooms with the criteria [15]. According to [15], the melanopic equivalent daylight illuminance (M-EDI) sufficiently describes human circadian light responses and throughout the daytime, the recommended minimum M-EDI is 250 lx in the vertical plane at approximately 1.2 m height. Unfortunately, this metric, as well as other recommendations for minimum levels of melanopic light in building interiors, does not say in which places the proposed criteria should be achieved and in which direction the vertical plane should be oriented. In a reference room with standard spectrally neutral glazing, M-EDI values in the center of the room on clear days reach significantly higher levels than 250 lx (Figure 9). In the middle of the tested room with glazing with very low melanopic light transmittance, the minimum M-EDI values are not reached under

clear skies at all (Figure 10). No direct sunlight penetrated the room during the measurements. In the tested room with glazing that transmits approximately 40% of photopic light, illuminances higher than 250 lx are achieved only near the window (Table 1). At a depth of 4 m from the window, the photopic illuminance of the vertical plane at a height of 1.2 m above the floor is only around 100 lx. Due to the very low transmittance of melanopic light through the glazing, the M-EDI values are well below the recommended minimum levels.

4 Conclusion

This article presents the results of photopic and melanopic illuminance measurements in two rooms under limited daylight conditions. Due to the objectives of the scientific study, within which the measurements of daylighting conditions were carried out, the melanopic transmittance of the glazing in one of the measured rooms was extremely low. Nevertheless, we can state that when evaluating the circadian effects of daylight, it is essential to take into account the spectral properties of glazing and indoor opaque surfaces. The measurements showed that even in conditions of relatively steady skylight, it is very problematic to evaluate the melanopic illuminance on the eyes of the users of the interior space. Light from computer screens increases the overall melanopic illumination on the eyes of a person working with a computer. This effect is quite pronounced in the depth of a room with very low melanopic daylight. The intensity of the illuminance of the eyes from the computer screen can be significantly higher in the depth of the room than the illuminance of the eyes with only daylight. The presented measurements show that spectrally neutral glazing with high photopic light transmittance has a high non-visual potential. In cloudy locations, in regularly occupied indoor spaces, the photopic light transmittance of 0.40 can be considered insufficient in most cases.
The measurements carried out also raised the question of whether, instead of year-round simulations with a range of subjective assumptions and their interpretations, it is not enough to adapt some of the traditional methods of designing and evaluating the daylighting of buildings in such a way that, in addition to the required photopic illuminance, the level of daytime melanopic illuminance is also guaranteed.

Acknowledgments

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