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The Effect of Internal Colored Surfaces on our Biological Response to Daylight: An Experimental Study

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Abstract

The discovery of the human biological response to light conditions, also known as the circadian efficiency of light, has recently become a frequent research topic. New medical facts emerged during the last decade proving that a long-term absence of biological response is associated with sleep disturbance, tiredness, increased incidence of chronic depression, bipolar disorder and seasonal affective disorder. The reason is the difference between the visual and biological (circadian) response to light and how it is being perceived by human beings: while the visual perception represented by the luminous efficiency function peaks at the wavelength of 555 nm, the circadian photoreception curve peaks in the blue light spectrum at ~450 nm. An experimental study was designed to confirm that the actual regulations, focusing solely on the visual comfort, may not be satisfactory as far as the biological stimulation is concerned. Four same sized models of an office room exposed only to natural daylight were manufactured, each having its internal surfaces painted by different combination of colors. The spectral distribution of light and illuminance were measured at positions along the room and the potential biological response of human beings was evaluated by an established model. The measurements showed that colored surfaces - especially yellow color - can provide satisfactory visual comfort, but simultaneously decrease the biological stimulation by daylight. Mainly in the winter period the biological response to daylight can be low even at medium illuminance levels. Thus, sufficient daylight and proper choice of internal surfaces' colors are important to avoid the potential negative health effects.

Keywords - circadian system; spectral characteristics of daylight; experiment in situ; colored surfaces

1. Introduction

Biological response to daylight presents the synchronization of our biological processes, such as the body core temperature regulation, metabolism, blood flow, sleep cycles, digestion and others with the day and

night cycle [1, 2]. These processes are known as the circadian rhythms, because they repeat approximately each 24 hours. The research of the biological response is related to the foundation of a non-visual photoreceptor ipRGC (intrinsically photosensitive retinal ganglion cells) in the retina, and it offers a new, more complex view on the evaluation of the indoor light climate in permanently occupied spaces [3].

The efficiency of biological stimulation depends on the amount and nature of light impinging on the retina. The requirements to achieve sufficient biological stimulation are more complex than those for visual perception, thus aiming only at fulfilment of visual comfort expressed by illuminance in lux may not be satisfactory [4]. The greatest risk is represented by the fact that the internal space can provide enough light for sufficient visual comfort, although the light conditions for biological stimulation may simultaneously remain inadequate.

Assessment of the biological stimulation is currently complicated due to the fact that the biological sensation of light is not an immediate effect, unlike the visual discomfort, and the health consequences of insufficient biological stimulation show up only after a long time of occupancy. In this study, the calculation algorithm designed by Rea et al. [5], based on the spectral power distribution (*SPD*) of light, spectral response curves of rods, cones and ipRGC and recognition of the blue-yellow channel, is employed. The aim of this study is to measure modifications in the *SPD* for office rooms with surfaces of different colors and evaluate the effect of these surfaces on the biological response of human beings to daylight.

2. Methodology

2.1 Evaluation of Biological Effects

The biological stimulation of human beings is strongly related to the regulation of sleep hormone melatonin during the day. Production of melatonin affects synchronization of sleep cycles, which in turn affects other biological processes, such as blood pressure, body regeneration, etc. Based on the regulation of melatonin secretion, the circadian photoreception curve can be defined as shown in Fig. 1 [5, 6]. The biological response can be evaluated by the normalized circadian light CL_A in circadian lux, which is a spectrally weighted *SPD*, representing the result of integration over the circadian curve $C(\lambda)$ (Fig. 1). It can be simplified considered as the biological equivalent of the photopic illuminance in photopic lux, which is the result of integration of *SPD* over the photopic curve $V(\lambda)$.

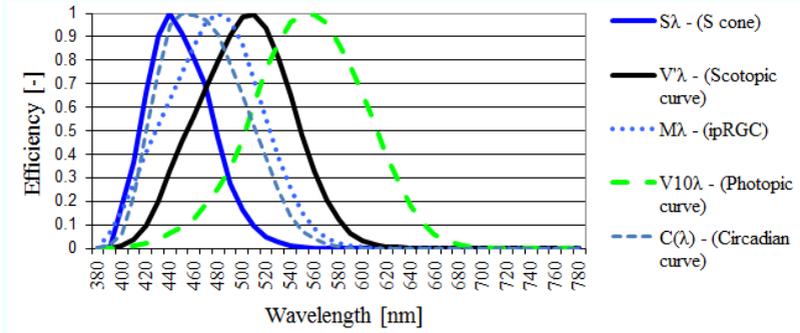


Fig. 1 Courses of spectral characteristics implemented into the computational method by Rea et al. [5] for biological human response to light

The normalized circadian light CL_A is calculated by the algorithm [5]:

$$\int \frac{s_\lambda}{mp_\lambda} E_\lambda d\lambda - k \int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda \geq 0 \quad (1)$$

$$CL_A = 1622 \int M_{c_\lambda} E_\lambda d\lambda \left(a_{b-y} \left(\int \frac{s_\lambda}{mp_\lambda} \Big|_{nm} E_\lambda d\lambda \right) - a_{rod} \left(1 - e^{-\left(\frac{\int V_\lambda E_\lambda d\lambda}{RodSat} \right)} \right) \right) \quad (2)$$

If equation (1) is not true, equation (3) should be used:

$$CL_A = 1622 \int M_{c_\lambda} E_\lambda d\lambda \quad (3)$$

where 1622 is a constant to normalize CL_A so that at 2856 K blackbody radiation and illuminance of 1000 lux the value of CL_A is 1000 circadian lux; E_λ is the light source spectral irradiance [(W/m²)/nm]; V_λ is the photopic luminous efficiency function [-]; V'_λ is the rod spectral efficiency function [-]; M_{c_λ} is the melanopsin-containing retinal ganglion cell spectral efficiency function (corrected for crystalline lens transmittance) function [-]; s_λ is the spectral sensitivity of S-cones [-]; $RodSat$ is the half-saturation constant for bleaching rods, equal to 6.5 W/m²; $d\lambda$ is the wavelength increment from 380 nm to 580 nm (780 nm); k is equal to 0.2616; a_{b-y} is equal to 0.6201; a_{rod} is equal to 3.2347; mp_λ is the macular pigment transmittance [-].

Light sources with a light spectrum dominated by the blue part provide higher levels of circadian lux than photopic lux. An exact minimum value of CL_A has not yet been specified, since many factors, such as age, race, locality, have to be considered and the influence of these factors vary. If visible light

is evaluated to achieve visual comfort, then biological light could represent a measure of psychological well-being. The maximum limit on CL_A varies depending on the season and the time of day. A clear blue sky during a summer day, when CL_A values in exterior often exceed 100 000 circadian lux, is beneficial for humans. In winter the sunshine is scarcer and the values of CL_A may become too low. In general, the higher the value of CL_A during the day, the “healthier” the indoor environment can be considered in terms of biological stimulation. However, this does not apply for nights, when a long-term exposure to excessive amount of CL_A during evenings and nights can result in insufficient sleep, chronic depression or a seasonal affective disorder [7].

Another quantity to measure the biological effect of light on human beings is the dimensionless circadian stimulus CS [-], which is a measure of how efficiently the light source can suppress melatonin secretion in humans [8]:

$$CS = 0.75 - \frac{0.75}{1 + \left(\frac{CL_A}{215.75} \right)^{0.864}} \quad (4)$$

The values of CS vary from 0.00 for no measurable suppression up to 0.75 for the most effective melatonin suppression. Suitable synchronization of circadian rhythms demands light conditions with the level of CS close to 0.75 during the day and CS close to 0 during the night time, when production of melatonin should peak.

2.2 Design of the Experiment

Four same sized room models were situated on the rooftop above the 5th floor of the Faculty of Civil Engineering in Bratislava, Slovakia. All models were exposed to natural daylight without any additional light source. The models were constructed in scale 1:5, with the dimensions of 600 mm × 600 mm × 1 500 mm, representing a real room with the dimensions of 3 000 mm × 3 000 mm × 7 500 mm (Fig. 2). Each model was equipped with a window with the dimensions of 400 mm × 300 mm, representing a real opening with the dimensions of 2 000 mm × 1 500 mm, facing South-East.

The present measurement was done on 15 January 2016 from 10:00 AM to 10:15 AM. The sky was overcast without direct sun light. Spectrophotometer Konica Minolta CL 500A was used to measure the spectral distribution of light and illuminance (Fig. 2).

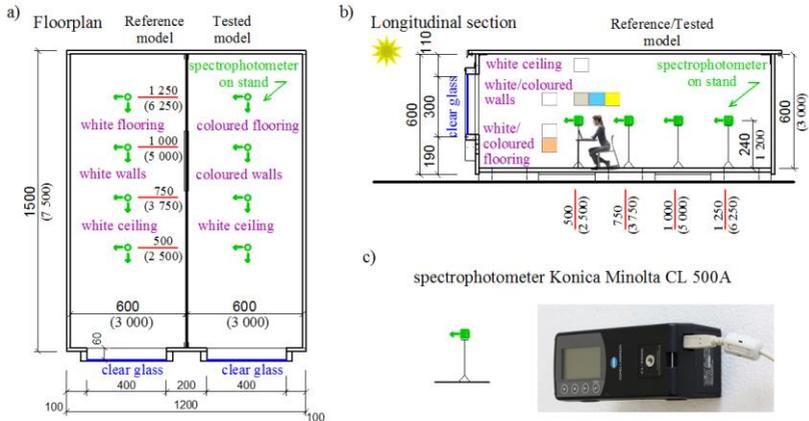


Fig. 2 Experimental layout and instrumentation: a) plan of the model, b) longitudinal section of the model, b) spectrophotometer to measure spectral distribution of light and illuminance

One model was marked as the „reference” with all surfaces white. The other three models were equipped with a light brown flooring, white ceiling and walls of various colors: light grey for the first model, light blue for the second model and yellow for the third model. The measurements of the *SPD* distribution were performed on a vertical plane at the height of sitting person’s eyes, i.e. at 240 mm above the floor, representing 1 200 mm in the reality. For each model the measurement was performed at the distance of 500, 750, 1 000 and 1 250 mm from the window, representing 2 500, 3 750, 5 000 and 7 500 mm in the reality, with the spectrophotometer’s sensor oriented to the window and to the wall for each measurement point.

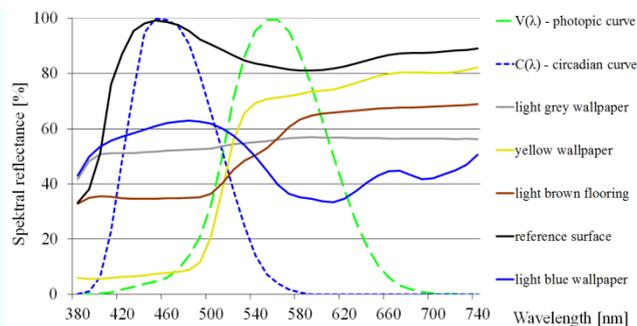


Fig. 3 Comparison of the relative spectral photopic and circadian reflectance for all surfaces

Before the experiment, relative spectral photopic and circadian reflectance of all the surfaces were measured in order to determine the

absolute reflectance of the internal surfaces. The absolute circadian and photopic reflectance (Table 1) was calculated by integration over the photopic curve $V\lambda$ and circadian photoreception curve $C\lambda$ shown in Fig. 3.

Table 1. Comparison of absolute reflectance for visual perception and circadian phototransduction

Coloured surface	Absolute reflectance	
	Photopic	Circadian
	ρ_V [-]	ρ_C [-]
yellow wallpaper	0.65	0.15
reference "refer" surface	0.85	0.87
light grey wallpaper	0.56	0.48
blue wallpaper	0.45	0.56
light brown flooring	0.56	0.34

3. Results

3.1 SPD Levels

The different SPD levels for all measured positions are shown in Figs. 4 and 5. The external SPD levels (Fig. 4a) can be compared with the SPD levels inside. Orientation of the sensor is indicated in the legend in parentheses.

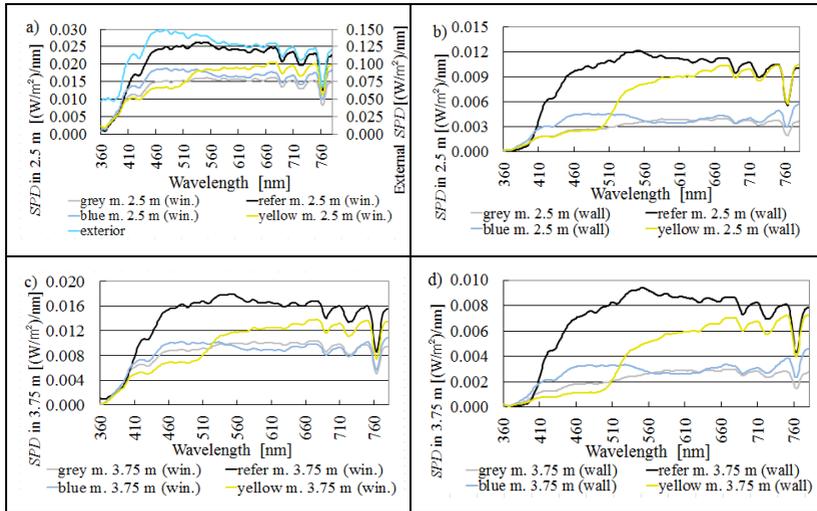


Fig. 4 Comparison of SPD levels for different positions and orientations (a-d)

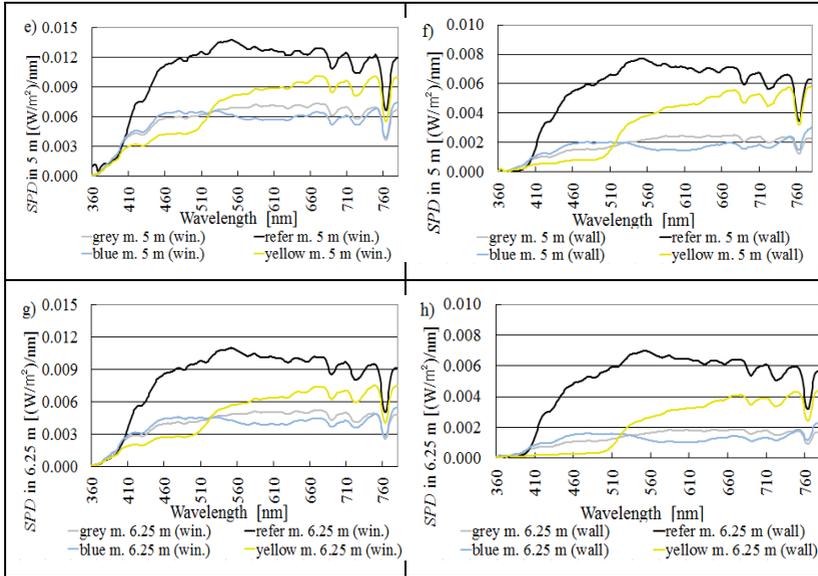


Fig. 5 Comparison of SPD levels for different positions and orientations (e-h)

3.2 Illuminance Levels

The levels of photopic illuminance are presented in Fig. 6. The external photopic illuminance was $\sim 10\,500$ lux.

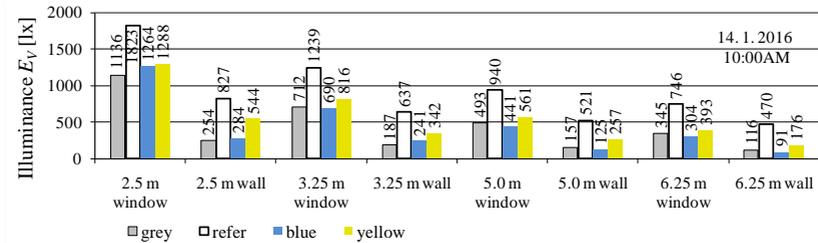


Fig. 6 Comparison of photopic illuminance for all positions and orientations of the spectrophotometer's sensor measured on vertical plane in height of eyes 1 200 mm

3.3 Circadian Light CL_A Levels

The levels of CL_A are presented in Fig. 7. The external circadian light level was $\sim 26\,500$ circadian lux.

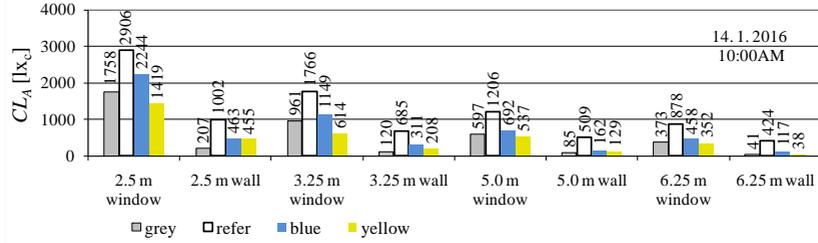


Fig. 7 Comparison of circadian light levels CL_A for all positions and orientations of the spectrophotometer's sensor

3.4 Circadian Stimulus CS Levels

The calculated CS levels are presented in Fig. 8. The level of CS in the exterior was 0.74.

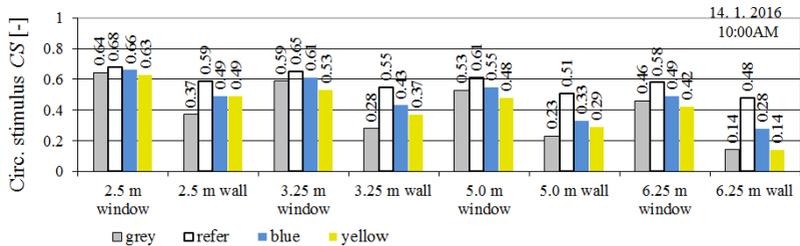


Fig. 8 Comparison of circadian stimulus CS levels for all positions and orientations of the spectrophotometer's sensor

4. Discussion

The smallest difference between the absolute photopic reflectance (0.85) and the absolute circadian reflectance (0.87) was recorded for white walls of the reference model, whereas the greatest difference was recorded for the yellow wallpaper, where the absolute photopic reflectance is 0.65 and the absolute circadian reflectance is 0.15 (Table 1). This is the reason for the differences between other visual and nonvisual parameters measured and computed in this experiment.

Figs. 4 and 5 show a significant reduction of the light spectrum dominated by the blue color for the yellow colored model. The greatest differences in *SPD* between the models were recorded with the sensor facing wall in the positions that are most distant from the window. However, filtration of the blue part of the light spectrum is already clearly visible in the position closest to the window (2 500 mm).

White surface of the reference model provides the greatest level of photopic illuminance on the vertical plane at 1 200 m above the floor,

followed by the model with yellow wallpaper, which also provides high photopic reflectance. This is because the curve of spectral reflectance of yellow wallpaper copies the shape of the photopic curve $V(\lambda)$.

The greatest values of CL_A were recorded for the reference model (Fig. 7) due to the highest absolute reflectance levels and to the fact that it is spectrally neutral, thus it homogeneously reflect all wave lengths. The model with yellow walls, which provided the second highest levels of photopic illuminance for all measurement positions, produced low values of circadian light levels CL_A . The model with grey wallpaper provided lower levels of CL_A than the yellow one, as well as it provided low levels of photopic illuminance. On the other hand, the curve of spectral reflectance of grey wallpaper is uniform, so the changes in spectrum of reflected light are also uniform.

At 2 500 mm from the window with the sensor facing the window the difference in CS in all models was negligible, as there was a great amount of direct daylight penetrating through the window directly into the sensor (Fig. 8). The values of CS were lowest for the grey model in all measurement positions with the sensor facing the wall. The CS values in models with blue and yellow wallpaper were almost the same, but the photopic illuminance was much higher for the model with yellow wallpaper, indicating that in rooms with blue walls lower levels of photopic illuminance are needed to provide the same level of biological stimulation. Differences in values of CS for different models are increasing with the distance from the window, as the direct view of the sky is increasingly restricted, and the effect of multiple light reflections between the surfaces of the model is becoming visible.

At 3 250 mm from the window the circadian illuminance is still high, which ensures higher CS values despite of the low efficiency of the ipRGC photoreceptors. However, with increasing distance from the window this is no longer true. The blue channel is closed and the yellow visual channel is activated. Since this moment on, only ipRGC photoreceptors are responsible for stimulation. Consequently, the levels of CS decline, as the condition in eq. (1) is no longer valid.

The relation between CS and CL_A is non-linear; although 3 250 mm far from the window with the sensor facing the wall the CL_A values are low, the values of CS are still relatively high. At the distance of 5000 mm and more both CL_A and CS values are very low; in these positions the biological stimulation is substantially lower than in positions closer to the window and the level of biological stimulation might not be sufficient at a long-term exposure.

The greatest filtration of blue part of light spectrum is in the yellow model with the sensor facing the wall. This is caused by the reflection of light from the internal walls. The blue part of the daylight spectrum is decreasing

at room depths that are commonly occupied by employees in offices. This might potentially result in insufficient biological stimulation.

5. Conclusion

The results of the present experiment emphasize the important effect of proper selection of internal surface color on the spectral characteristics of natural daylight penetrating through a clear window glass. This is best illustrated by the case of the model with yellow walls: although the greatest values of photopic illuminance were recorded for the reference model and the model with yellow walls, the natural light spectrum of the model with yellow walls was substantially modified due to filtration of the blue part of light spectrum, with a possible negative impact on biological stimulation. Thus, incorrect choice of internal surface color could significantly decrease biological stimulus despite high values of photopic illuminance. This fact should be taken into account during the design stage of spaces for long-term occupancy. The spaces with greater depth and smaller windows should be equipped by light surface colors, such as white or light grey to provide uniform spectral reflectance. On the other hand, yellow surfaces should not be used, as they eliminate the blue part of daylight spectrum. Despite the number of studies focused on non-visual effects of light on human beings, a complex evaluation method is subject to further research.

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