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External lighting and the issues of mesopic vision

***Abstract**. This article presents an analysis of the influence of mesopic vision conditions on the reception of light impressions in external spaces. The primary emphasis in the conducted research is on the comparison of light sources selected for examination. The article presents the indicators enabling the assessment of light sources and conclusions drawn based on the conducted analysis.*

***Streszczenie.** W niniejszym artykule została przedstawiona analiza wpływu warunków widzenia mezopowego na odbiór wrażeń świetlnych w przestrzeniach zewnętrznych. Główny nacisk w prowadzonych badaniach kładzie się na porównanie wybranych do badań źródeł światła. W artykule zaprezentowano wskaźniki umożliwiające ocenę źródeł światła oraz wnioski wysnute na podstawie przeprowadzonej analizy. (**Oświetlenie zewnętrzne i problemy widzenia mezopowego**).*

Keywords: mesopic vision, elf factor, s/p factor, external lighting.
Słowa kluczowe: widzenie mezopowe, współczynik elf, współczynnik s/p, oświetlenie zewnętrzne.

Introduction

The Nobel Prize awarded in 2017 in the field of Physiology or medicine, revived questions about the impact on health and well-being of the human population, defined not only as of the intensity of illumination. One of the problems that have been raised is the correctness of the use of the same guidelines in photopic conditions as scotopic or mesopic. The limit of mesopic vision is determined for the luminance value 3 cd/m^2. It is worth paying attention to the values specified in PN-EN 13201-2: 2016 for M classes, they are below this value.

To determine the level of influence of changes in lighting conditions on the perception of the luminance value, you can use a factor S/P, defined later in this article.

Photoreceptor cells

Light-sensitive cells (specialised retinal neurons) divided into rods and cones. As a result perception of the electromagnetic wave in the visible range, i.e. 390 nm to 790 nm, photochemical cells produce two types of photosensitive pigment. Rhodopsin is produced in suppositories, while iodopsin in rods. The intensity of the secretion of individual pigments is closely related to the luminance reaching the retina of the eye. Based on the activity of individual photoreceptors, the following types of vision are discriminate: scotopic - focused on contrast, mesopic - transitional and photopic - designed for colour recognition. At the same time, as the intensity of light decreases, the ability to distinguish colours decreases. The more rods they take in recognising light stimuli, the more they darken the colour red, and the blue ones acquire brightness [1, 2].

The vision expressed in the equations

Mathematically determine the amount of energy reaching the retina, values shall be calculated using standard quantities like luminous flux ϕ_e, luminous spectral efficiency function $V(\lambda)$ and maximum of luminous efficacy of radiation K_m:

$$\phi = K_m \int_{380}^{780} \phi_{e,\lambda}(\lambda) V(\lambda) d\lambda \tag{1}$$

where: ϕ_e – luminous flux (W), K_m – maximum of luminous efficacy of radiation (lm/W), $V(\lambda)$ – spectral luminous efficiency function, λ – wavelength (nm).

The International Commission for Lighting CIE issued a recommendation that the spectral luminous efficacy under mesopic conditions should be determined based on the photopic spectral luminous efficiency function V (λ) and the function scotopic spectral luminous efficiency function V '(λ). This procedure allows you to allow the human eye sensitivity should be taken. It is worth noting that the curve of the eye's sensitivity in mesopic vision conditions has no specific shape, but changes for smoothly with a change in the luminance level between the photopic and scotopic functions of the luminous spectral efficiency [3]. The linear gradient of luminance changes in mesopic conditions can be determined using equation 2:

$$M_{(m)} \cdot V_{mez} = m \cdot V(\lambda) + (1-m) \cdot V'(\lambda) \quad for\, 0 \le m \le 1 \tag{2}$$

where: $M(m)$ – normalizing function such that V_{mez} attains a maximum value of 1, m – factor, the value of which depends on the conditions of visual adaptation: $m = 0$ for $L_{mez} < 0.005$ cd/m^2; $m = 1$ for $L_{mez} > 5$cd/m^2.

Also, the value of mesopic luminance L_{mez} is calculated according to the regulations published by The International Commission for Lighting CIE by the following formula:

$$L_{mez} = \frac{K_m}{V_{mez}(\lambda_0)} \int_{380}^{780} V_{mez}(\lambda) L_e(\lambda) d\lambda \tag{3}$$

where: $V_{mez}(\lambda_0)$ – the value of the V_{mez} function at a wavelength of 555 nm, K_m – luminous efficacy of radiation, $K_m = 683$ lm/W at a wavelength of 555 nm, $L_e(\lambda)$ – the spectral radiance (W/m^2·sr·nm).

Mathematical description of the S/P factor

Most lighting situations in which a person performs visual work takes place in photopic conditions, where suppositories react to light stimuli. For this reason, most of the generally available measuring instruments are calibrated using photopic spectral luminous efficiency function $V(\lambda)$. However, as mentioned at the beginning, in the case of visual work carried out outdoors, for example driving on the surface of the roadway, lighting conditions force the eye to work in transient conditions, i.e. in mesopic conditions. In this case, the obtained results turn out to be falsified, because they are determined for photopic eye sensitivity, in other words, using a spectral luminous efficiency function that is not adapted to the conditions. To visualise and correct the determined values of the determined luminous flux, the so-called S/P ratio [4]. The S/P ratio is defined as the ratio of luminous flux values in scotopic conditions to luminous flux values in photopic conditions, as shown by equation 4:

(4) $$S / P = \phi_s \; / \; \phi_p$$

where: ϕ_S – luminous flux in scotopic conditions (W), ϕ_p – luminous flux in photopic conditions (W).

Mesopic vision in external lighting

Requirements specifying the average minimum luminaire illumination included in the PN-EN 13201-2: 2016 standard are in the range of 0.3-2 cd/m^2. According to experts in medical sciences, mesopic vision begins with luminance values below 3 cd/m^2, which includes guidelines for road lighting standards. Based on the concept of luminance, an iterative calculation method was developed, shown through dependence 5. To obtain a fast convergence of results is recommended to start calculations with a value of the factor m of 0.5 [4].

(5) $$L_{mez} = \frac{m_{n-1} \cdot L_p + (1 - m_{n-1}) \cdot L_s \cdot V'(\lambda_0)}{m_{n-1} + (1 - m_{n-1}) \cdot V'(\lambda_0)}$$

$$m_n = 0.767 + 0.3334 \cdot \log_{10} \cdot (L_{mez,n})$$

where: ϕ_S – luminous flux in scotopic conditions (W), ϕ_p – luminous flux in photopic conditions (W).

It should be mentioned here that considering only the S/P ratio does not reflect the full picture of changes taking place during the turn of light conditions affecting the human body. The process is a bit more complicated. Under mesopic conditions, the range of the most distinct field of view changes. Due to the distribution of rods in almost the whole surface of the retina - except for the central well, it is possible to perceive objects located on the edge of the field of view, which is impossible in photopic vision. The measuring grid used to verify the correctness of the choice of lighting is adapted to photopic conditions, i.e. for a very narrow range of the most intense view [5, 6].

For this reason, it is also necessary to analyse the correctness of the selection of the grid of measuring or computing points. Another process that should be taken into account is the time needed to adapt the eye to reduced light intensity, for example when leaving a well-lit building. The action of adaptation to the dark, in contrast to the swift adjustment to brightness, lasts at least a few minutes [7].

Measurement methodology

To carry out the calculations were necessary to obtain spectral distributions of real light sources. It was decided to test the most common conventional luminaires in Poland: low-pressure sodium luminaire and high-pressure sodium luminaire, and compare them with LED luminaires used in modernisations and new projects with cold colour temperature. The Konica Minolta CS-2000 spectrometer was used for the measurements, while the CS-S10w software installed on the computer was used to visualise the data. The measurements were carried out following the guidelines provided in document CIE 121-1996. Based on the obtained data and the formulas quoted earlier, graphs were generated showing the distributions of spectral irradiance. The charts were prepared for each of the measured light sources, taking into account the curves of the eye sensitivity in photopic and scotopic conditions. Figures 1 and 2 show the results for the LED lamp.

Next, the S/P ratio was specified using the dependency determined based on formulas 4 and 1:

(6) $$S / P = \frac{K'_m \int_{380}^{780} S_\lambda(\lambda) V'(\lambda) d\lambda}{K_m \int_{380}^{780} S_\lambda(\lambda) V(\lambda) d\lambda}$$

where: K'_m – the maximum of luminous efficacy of radiation in scotopic viewing conditions for the wavelength 507 nm, K'_m = 1700 lm/W, $V'(\lambda)$ – the CIE scotopic spectral luminous efficiency function, K_m – the maximum of luminous efficacy of radiation in scotopic viewing conditions for the wavelength 555 nm, K_m = 683 lm/W, $V(\lambda)$ – the CIE photopic spectral luminous efficiency function, S_λ – spectral characteristics of the light source.

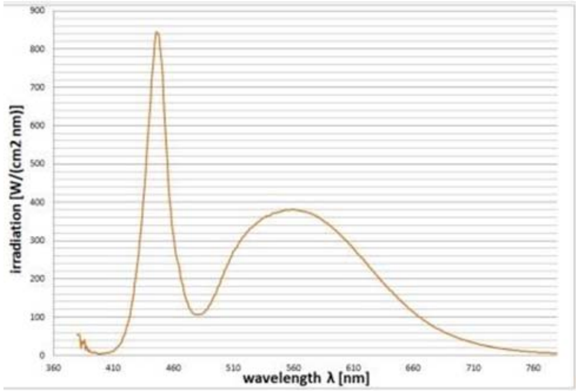

Fig.1. The spectral distribution of irradiation of the LED lamp

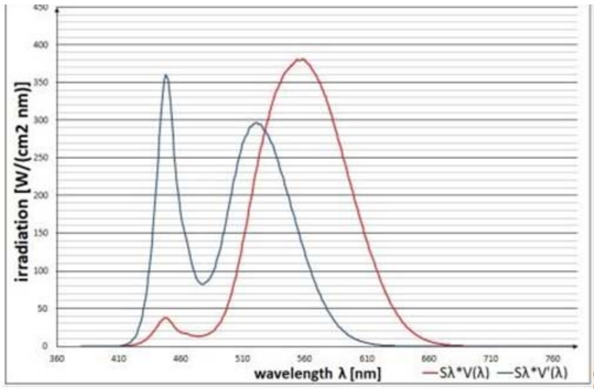

Fig.2. The spectral distribution of the LED lamp irradiation taking into account the sensitivity of the eye

Comparing figures 1 and 2 can be seen dissimilarity between the distribution of the spectral irradiation of the lamp without and taking into account the sensitivity of the eye in the conditions of photopic and scotopic vision. According to predictions, under scotopic conditions, stimuli associated with the blue spectrum of light are more strongly received. In contrast, the red range is seen less well than in photopic terms [8].

Table 1 presents the calculated values of coefficients S/P for light sources selected for the experiment.

Table 1. Summary of values S/P factor

Name of the luminaire	*Value of S/P factor*
low-pressure sodium	0.24
high-pressure sodium	0.51
LED 4000K	1.66
LED 5700K	2.05

Calculating of luminance in mesopic conditions

To determine the value of the luminance for the mesopic conditions, used iterative according to formula 7 which is a converted correlation 5:

(7) $$L_{mez} = \frac{m_{n-1} \cdot L_p + (1 - m_{n-1})(S / P) \cdot K}{m_{n-1} + (1 - m_{n-1}) \cdot K}$$

where: K – factor whose value is 683/1699, S/P – S/P ratio based on the measurement; $m_n = 0.767 + 0.3334 \cdot \log_{10}(L_{mez,n})$

Calculating of ELF ratio

After determining the value of the mesopic luminance can be defined ratio of the luminance to the mesopic luminance of the photopic luminance by using the following formula:

(8) $$ELF = L_m / L_p$$

The above determinant of Effective Luminance Factors determines the efficiency of lighting in mesopic vision conditions regarding photopic vision conditions.

Table 2.Summary of results of the calculation for the adaptation luminance 1cd/m^2

Name luminaire	*The value of mesopic luminance L_m*	*The determinant value ELF*
low-pressure sodium	0.91	0.91
high-pressure sodium	0.94	0.94
LED 4000K	1.07	1.07
LED 5700K	1.11	1.11

To allow easier comparison of the subjective luminance received by photoreceptors in the mesopic conditions and to highlight whether the perceived value is smaller or larger than the assumed amount, the percentage Effective Luminance Factors, i.e. ELF% was introduced. The amount of ELF% is calculated by reference to luminance in photopic conditions the difference between luminance in mesopic terms and related to luminance in photopic states, as shown in formula 8.

(8) $$ELF\% = \frac{L_m - L_p}{L_p}$$

The calculations were carried out for roadways in the M road class. Normative values of luminance for road classes M are shown in Table 3 [9]. The values of the ELF% coefficient for individual classes M are presented in Table 3.

Table 3.Summary of results of the calculation for the adaptation luminance 1cd/m^2

class	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**
L [cd/m^2]	2	1.5	1	0.75	0.5	0.3

Table 4. Summary of values ELF% factor for tested luminaires including road classes

Name luminaire	*low-pressure sodium*	*high-pressure sodium*	*LED 4000K*	*LED 5700K*
S/P	0.24	0.51	1.66	2.05
Road class				
M1	-5.76	-4.79	0.0	0.15
M2	-7.56	-5.80	0.83	2.72
M3	-9.70	-5.93	6.43	9.59
M4	-10.58	-6.00	12.81	16.84
M5	-10.11	-7.50	24.79	29.62
M6	-15.74	-12.25	42.39	47.19

Conclusions

At the conclusions from Table 1, it can be seen that the S/P ratio is directly related to the colour temperature of the light source. A higher value of the colour temperature of the light source determines a higher S/P ratio. Also, comparing the values placed in tables 1 and 2, it was found that the higher the S/P ratio, the higher the relative luminance value under mesopic conditions. Given the results presented in Table 4, found that the coefficient when the S/P ratio is below unity, the human eye under mesopic conditions receives luminance below the assumed level, while for the S/P ratio above one, the luminance perceived by the human eye may be approx. 40% higher than expected based on data obtained in photopic conditions. It is visible that using a light source with a warm colour temperature the error resulting from the adoption of photopic terms reaches a maximum of 15%.

A great example of visualisation of data obtained in the table is the lighting of parks. Until now, the open spaces of the parks were illuminated with sodium sources which are perceived by the eye as delicate and perceived with about 1/10 smaller stream than in photopic conditions. Due to the shallow colour rendering due to the high chromaticity of the light source, most of them are exchanged for LED light sources with a colour temperature of 4000K and more upper. It would appear to be common sense for luminaires to be the same in terms of the value of the stream and the distribution of light. However, after replacing the sources of light, it turns out that the park seems much clearer, and the residents sometimes complain about sleep problems. Much higher brightness is related to the Purkinje effect, while Table 4 shows the level of difference between these luminaires - at the lowest luminance 0.3 cd/m^2, it can be as high as 60%.

What would happen if we tried to adjust the luminous flux to mesopic conditions? Based on the data in Table 4, can see that after taking into account the ELF coefficient, the required lighting conditions can achieve at the lower power of the light source. The assumption of the consideration of mesoporous phenomena doesn't justify by the case of luminosity larger than 1cd/m^2, where the change in stream perception does not exceed several percents. However, when the ambient luminance falls below 1cd/m^2, the mesopic phenomenon begins to play a significant role, and the colour temperature and spectral distribution of the light source selected for lighting the road start to play a notable role. Let us consider the case that the source of light used for space lighting has an S/P ratio of 1.5, and the required normative luminance of the road is 0.75cd/m^2. Based on the calculations made in the previous point, assume that the ELF% for the presumed conditions is about 12%. Means that in the mesopic view, the human eye perceives the luminance of the environment by 12% more than in terms of photopic vision, the parameters of the standard will be meeting at 88% of the luminance value received under photopic conditions. Because the change in luminance is directly proportional to the evolution of the luminaire flow, and the turn of the stream to the power of the luminaire, it can be assumed in a simplified way that obtains the appropriate value of subjective luminance, the power should be reduced by the same percentage. However, with a wide range of methods for controlling LED sources, adapting the luminaire to any lighting situation should not cause problems. If the dynamics of research on LEDs continues to maintain high pace, and the luminous efficiency of LED light sources will continue to grow, while the prices fall, LED sources will completely overpower the exterior spaces. Besides, increased durability of LEDs appeals to investors, and once more the number of lighting manufacturers resigns from conventional solutions. When collecting materials for the article, noted that the leading lighting manufacturers are beginning to be interested in information on mesopic vision and start conducting training and information campaigns on the S/P ratio. Also in some catalogue cards, information about the value of S/P or ELF for a particular luminaire begins to appear.

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