Visual Perception in External Lighting Conditions

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Abstract

LED street lighting is a topical trend in modern outdoor lighting. High light output of LEDs creates all conditions for modernization of electric lighting networks in Ukraine. Human vision is a complex process associated with retinal light perception. Vision is divided into: day vision, night vision, and twilight vision. The function of the eye is highly dependent on the distribution of brightness in the field of vision. The spectral sensitivity of photoreceptors varies for different wavelengths of the visible spectrum and different levels of light intensity. The rationing of the lighting installation is based on detailed studies of the observer's visual performance depending on different lighting conditions. One of the main luminous parameters that can easily be measured objectively is illumination. Brightness as a function of illumination, the observer's position and the spectral coefficient of the working surface reflection is more informative, but has some difficulty in measuring. There is a clear need to develop a system that would make it possible to uniquely assess the visual efficiency of a given spectral composition under certain observation conditions. It was decided to introduce the term equivalent brightness as the parameter of such a system. The difficulty of using the function $V_{ek}(\lambda, L_{ek})$ to calculate the equivalent brightness is the function's dependence $V_{ek}(\lambda, L_{ek})$ on L_{ek} . The aim of the study is to approximate the function of the relative spectral luminous efficiency in mesopic regions by a set of standard CIE functions that do not depend on the value of equivalent luminosity. The calculation method $V_{ek}(\lambda, L_{ek})$ is proposed using only two normalized functions of the relative spectral radiation efficiency for day $V(\lambda)$ and night $V'(\lambda)$ vision. The use of such approximation function makes it possible to determine the equivalent brightness, which adequately reflects the level of visual perception under the conditions of ambient illumination, based on the photometric brightness of the light source. To calculate $V_{ek}(\lambda, L_{ek})$ we use the ICE recommended functions of relative spectral light efficiency for the twilight vision, which are based on the spectral composition of the blackbody radiation with a color temperature of 2042 K. The use of the developed methodology provides results that more accurately characterize the efficiency of light sources in outdoor lighting installations compared to the results of calculations obtained when using standard methods.

INTRODUCTION

Lighting in Ukraine uses 15–20% of the electricity produced by all the country's power plants, with the overall efficiency of fuel conversion to light energy being about 3% [1].

The stage of modernization of the lighting industry will make it possible to create energy efficient lighting that will meet the requirements of CIE standards. Above all, the basis for energy saving should be the replacement of inefficient light sources with energy-efficient ones [2, 3].

LED street lighting is today a progressive direction in the area of beautification of settlements and highways outside their limits. LED street lighting is absolutely deservedly considered to be a current direction in the sphere of modern outdoor lighting [4, 5]. High light output of LEDs with low energy consumption in conditions of their competent maintenance creates all prerequisites for the modernization of electric lighting networks of urban areas and highways in Ukraine [6, 7].

At the same time, lighting technology is moving to a new level, becoming increasingly complex, therefore the help of specialists in selection of lighting means, design of modern lighting complexes,

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creation of optimal light environment and lighting design, the principles of energy conservation are becoming increasingly important for the consumer [8, 9]. The need to introduce them into the lighting system is obvious, but requires a deeper professional understanding, theoretical soundness and experimental testing of photometric performance. Behind the high rates, it is difficult to see the negative impact of hidden factors that are insufficiently understood and sometimes unforeseen. Therefore, it is important not only to introduce modern light sources, but likewise to use optical radiation of the lighting system in a cost-effective way, which will allow an efficient light environment to be created.

VISUAL PROCESS

Human vision is a complex process associated with retinal light perception. When light hits the retina, it affects the photosensitive cells: three kinds of cones and rods. The excitement caused by its effect is then transmitted through the optic nerve to the brain. Photoreceptor arousal process is not linear and depends on many parameters, primarily on the physical features of the retina. In total, the retina contains approximately 130 million rods and more than 7 million cones [10] which vary in shape as well as in properties. The rods are long and thin cells oriented along the axis of light passage located throughout the retina with a zone of maximum concentration thereof at a distance of 10–12° from the center (on the periphery). Cones are short conical cells, concentrated in the central area of the retina with maximum concentration in the central fovea of the eye [11].

The eye is able to distinguish small image details only by the central part of the visual field at an angular size of 1.3–1.5°. Therefore, central vision is also called cone vision. Peripheral vision corresponds more to rods, as they are distributed in the peripheral zone.

Vision is also divided into day, night and twilight vision (cones and rods work together).

Rod vision (night vision) has the highest sensitivity to light at low luminosity levels (below 0.1 cd/m²), but cannot convey a sense of chromaticity. Conical (daytime) vision provides color vision, but it is significantly less sensitive to weak light and fully functional only at brightness levels above 10 cd/m². This is due to the fact that the rods are attached to the nerve fibers in groups of several tens and hundreds, and the cones are attached almost individually (usually no more than two or three elements per fiber). The rod group reacts more slowly to light than one or two or three cones. The main advantage of the group connection is that it is more sensitive to light. Daytime vision is characterized by high visual acuity, good visual perception of

the color and shape of the object, while night vision is responsible for orientation in space [12].

The rate of adaptation of night vision photoreceptors to changes in brightness is much slower than that of the day vision photoreceptors. So the eyes tend to get used to the darkness more slowly. And as soon as one moves from a dark room to a light one, day vision is immediately activated.

It is important to note that the photoreceptor spectral sensitivity varies for different wavelengths of the visible spectrum and different levels of light intensity. Night vision, for example, is most sensitive in the emerald-green part of the spectrum, so emerald color appears brighter at dusk than all the rest.

REGULATORY FRAMEWORK AND INTERMEDIATE LIGHTING

As is known, the rationing of the lighting installation is based on detailed studies of the observer's visual performance depending on different lighting conditions. One of the main luminous parameters that can easily be measured objectively is illumination. To a great extent, the choice of this parameter is precisely the ease of its control. To select the necessary levels of illumination, different criteria are used: visibility of the object of distinction, observers' subjective assessments, and technical-economic indicators. But more often than not, it is visual performance, sometimes coupled with exhaustion. A large number of studies were aimed at determining the visual function with regard to illumination, which made it possible to use this parameter quite effectively. It has been proved that as the illumination increases, the productivity and quality of the visual performance increases, and fatigue decreases. When the size of the comparison objects is reduced, the dynamics is sharper.

However, given that visual sensation is a function of brightness, its distribution in the field of vision and the spectral composition of radiation, it is understandable that illumination is not a sufficient characteristic to describe the field of vision, even taking into account the **integral reflectance**, as the spectral characteristics of surfaces and light sources remain unaccounted for.

Brightness as a function of illumination, the observer's position and the spectral reflection coefficient of the working surface is more informative, but has some difficulties in measuring. Research and regulation of illumination quality indicators are often associated with the distribution of brightness in the field of vision. Significant progress has been made in the transition to the regulation of the discomfort index. Visual discomfort is defined as the feeling of awkwardness and tension caused by the

presence of direct and reflected brilliance in the illuminated space.

To limit direct brilliance, the rules of some countries, including Ukraine, apply a glare indicator determined by the brightness of the lamp and its geometrical position relative to the observer. The new European international standards regulate the UGR (unified glare rating) composite index of discomfort, which takes into account all lamps that create a direct blinding glare on the observer. It should be noted that the results of both methods are quite similar. The contrast ratio CRF (contrast rendering factor), which is calculated on the basis of software tools, was introduced to characterize the reflected brightness of CIE.

Light action on a human is determined, on the one hand, by quantitative and qualitative parameters of the light medium, on the other hand - by regularities of physiological optics, developmental anatomy, psychophysiological vision and photobiology. The most striking area of the optical spectrum for humans is visible light (380–780 nm) [13].

It is known that the brightness and luminosity of the roadway is regulated. Levels of brightness of the road surface are defined within the range of 0.2–1.6 cd/m² depending on the street category.

Levels of brightness for external illumination are taken based on the properties of the surface in dry weather, i.e. under normal driving conditions (NDC). According to the conducted in 2007 Ekrias and Castillo measurements, the level of the road surface visibility [14], the visibility distribution created by different illumination installations varies significantly depending on different weather conditions. For example, in rainy weather, the brightness of the road surface with a mirror reflection in the direction of the driver's line of vision increases in comparison to that in normal driving conditions, while the brightness of the dark road tracks decreases. The increasing uneven brightness of the roadway surface leads to a deterioration in visibility conditions. Moreover, the average brightness level of the wet roadway surface increases. In snowy weather, the brightness of the road surface can be several times greater than that under the NDC. It turned out that for all weather conditions the brightness range usually does not exceed 5 cd/m² and lies in the area of twilight vision.

While driving, the driver usually looks straight ahead, and if there is an obstacle on the road along the path of automobile movement, then its image gets into the driver's central field of view, into the day vision. But obstacles can also arise in the periphery, in the joint area of night and day vision. The ability to detect mobile objects in both central and peripheral areas is an important part of the driver's visual activity. Its importance increases especially at night [15]. In the conditions of twilight

vision, it is known that the detection of moving objects on the periphery when illuminated by sources with a blue spectrum (shifted into a short wave region) is better than with a reddish one (shifted into a long-wave region) [16, 17]. This result showed that rods (and thus night vision) are responsible for the process of detecting moving objects. Thus, the driver's visual problem can be divided into at least four problems: identification of obstacles in the central field of vision; perception of the brightness distribution in the field of view of obstacle detection on the periphery; detection of moving objects [18]. When traveling on a night city, architecturally illuminated objects with a brightness of 3–30 cd/m² are visible.

The eye functioning is highly dependent on the distribution of brightness in the field of vision. In the absence of directional lighting of urban facilities, all other streets of category A and B can be included in the same area. At brightness levels of more than 5 cd/m², the photoreceptors of daytime vision contribute significantly to the visual process. In other words, the higher the brightness of the objects in the driver's visual area, the greater the sensitivity of cones and the smaller the nighttime photoreceptors. Therefore, practically all streets with bright architectural illumination belong to the area of daytime vision, and most streets without architectural illumination belong to the area of twilight vision. And the choice of light sources to illuminate the streets should be based primarily on their visual efficiency depending on the conditions of vision.

APPROXIMATION OF THE SPECTRAL SENSITIVITY OF THE EYE IN THE TRANSITION AREA OF ADAPTATION

In classical photometry, that is, at the brightness of the adaptation according to day vision, the basis for determining the illumination efficiency is the function of the relative spectral luminous efficiency of radiation for the light-adapted eye of a standard observer. If the luminosity level is already reduced to 10 cd/m², there is a slight deviation of the spectral luminous efficiency of the radiation relative to the visual apparatus from the specified function. In some adaptation environments, such as outdoor lighting, nighttime driving, and driving in mines and tunnels, it is quite difficult to determine the efficiency of multispectral light sources. After much discussion of the light engineering community, it became clear that there was a need to develop a system that would enable to clearly assess the visual efficiency of the light source of a given spectral composition under certain observation conditions. It was agreed to introduce the term equivalent brightness as a parameter for such a system. Despite numerous studies, the methods used to determine this

parameter are quite laborious and do not take full account of the patterns of visual perception of twilight vision.

During the transition from dark to light adaptation of the eye, the spectral sensitivity of the eye changes continuously: the wavelength is shifted, representing the maximum sensitivity [19]. The most complete picture of the visual effect of light in the transition region between day and night visions gives the value of equivalent luminance [20, 21]. The evaluation of the level of photometric luminance at small levels of adaptation is not rational, as the intensity of the light perception of the visual apparatus in this case can vary by orders of magnitude, depending on the spectral composition of the radiation [22]. The difficulty of using the $V_{ek}(\lambda, L_{ek})$ function to calculate the equivalent brightness consists in the dependence of the $V_{ek}(\lambda, L_{ek})$ function on L_{ek}

$$V_{ek}(\lambda, L_{ek}) = K_1(\lambda, L_{ek})V'(\lambda) + K_2(\lambda, L_{ek})V(\lambda). \quad (1)$$

To calculate $V_{ek}(\lambda, L_{ek})$ they use the recommended by CIE in 1963 the functions of relative spectral luminous efficiency for twilight vision (Fig. 1) based on the spectral composition of black body radiation at a color temperature of 2042 K [23]. Coefficient values $K_1(\lambda, L_{ek})$ and $K_2(\lambda, L_{ek})$ is:

$$K_1(\lambda, L_{ek}) = \frac{V_{ek}(\lambda, L_{ek}) - V(\lambda)}{V'(\lambda) - V(\lambda)}, \quad (2)$$

$$K_2(\lambda, L_{ek}) = \frac{V_{ek}(\lambda, L_{ek}) - V'(\lambda)}{V(\lambda) - V'(\lambda)}. \quad (3)$$

There are minor deviations in the proximity of the maximum spectral sensitivity (Fig. 2) in terms of negative coefficient values K_1 and K_2 .

Let us consider the example of calculating $K_2(\lambda, L_{ek})$ at $L_{ek} = 0.1 \text{ cd/m}^2$:

$$\begin{aligned} K_2(520 \text{ [nm]}, 0.1 \text{ [cd/m}^2]) &= \\ &= \frac{V_{ek}(520 \text{ [nm]}, 0.1 \text{ [cd/m}^2]) - V'(520 \text{ [nm]})}{V(520 \text{ [nm]}) - V'(520 \text{ [nm]})} = \\ &= \frac{0.96 - 0.935}{0.71 - 0.935} = -0.111, \end{aligned}$$

since $K_1 + K_2 = 1$, we have:

$$K_2(520 \text{ [nm]}, 0.1 \text{ [cd/m}^2]) = 1 - (-0.111) = 1.111.$$

Negative values K_2 in the central wavelength range (Fig. 3) are due to the fact that in the intermediate region bounded by segments 1 and 2 (Fig. 2), the numerator $(V_{ek}(\lambda, L_{ek}) - V'(\lambda))$ has a positive value, and the $(V(\lambda) - V'(\lambda))$ denominator has a negative value, since the function of the relative spectral luminous efficiency for the night vision $V'(\lambda)$ has reached the maximum spectral sensitivity

then intersects with $V_{ek}(\lambda, L_{ek})$. But in this study, it is not essential which sign the coefficients have, since we are interested in the resulting value $V_{ek}(\lambda, L_{ek})$ using two normalized functions $V(\lambda)$ and $V'(\lambda)$, which coincides absolutely with the recommended CIE functions.

For further calculation, we'll determine the average values of the spectral coefficients $K_1(\lambda, L_{ek})$ and $K_2(\lambda, L_{ek})$ by the formula:

$$K_1(L_{ek}) = \frac{1}{n} \sum_{i=400 \text{ [nm]}}^{700 \text{ [nm]}} K_{1_i}(\lambda, L_{ek}), \quad (4)$$

$$K_2(L_{ek}) = \frac{1}{n} \sum_{i=400 \text{ [nm]}}^{700 \text{ [nm]}} K_{2_i}(\lambda, L_{ek}), \quad (5)$$

where $n = 16$.

Taking into account Eq. (4) and (5), the expression gives a fairly accurate description of the variation of the spectral efficiency of radiation in mesopic regions:

$$V_{ek}(\lambda, L_{ek}) = K_1(L_{ek})V'(\lambda) + K_2(L_{ek})V(\lambda). \quad (6)$$

Let's determine the CIE coefficients $K_1(\lambda, L_{ek})$ and $K_2(\lambda, L_{ek})$ for $L_{ek} = 10^{-3}; 10^{-2}; 10^{-1}; 1; 10 \text{ cd/m}^2$. The calculated values are given in Table 1.

The functions of the coefficients $K_1(L_{ek})$ and $K_2(L_{ek})$ are defined using regression analysis in the Mathcad Prime environment and in the range of $L_{ek} = 10^{-3} \dots 10 \text{ cd/m}^2$ are represented by expressions:

$$\begin{aligned} K_1(L_{ek}) &= -0.003(\log L)^4 + 0.033(\log L)^3 + \\ &+ 0.13(\log L)^2 - 0.24 \log L + 0.151, \end{aligned} \quad (7)$$

$$\begin{aligned} K_2(L_{ek}) &= 0.003(\log L)^4 - 0.033(\log L)^3 - \\ &- 0.13(\log L)^2 + 0.24 \log L + 0.849. \end{aligned} \quad (8)$$

After the approximation we obtain the dependencies given in Fig. 4, it is clear that the curves of functions $K_1(L_{ek})$ and $K_2(L_{ek})$ pass precisely through the fixed values of the coefficients $K_1(L_{ek})$ and $K_2(L_{ek})$ derived based on $V_{ek}(\lambda, L_{ek})$ of the CIE.

Theoretical studies have shown that at the approximation $V_{ek}(\lambda, L_{ek})$ as a superposition of normalized curves of relative spectral luminous efficiency for day $V(\lambda)$ and night vision $V'(\lambda)$, an error created by multispectral light sources does not reach 0.006% (Fig. 5). Functions $V(\lambda)$ and $V'(\lambda)$ using the factors $K_1(L_{ek})$ and $K_2(L_{ek})$ with high accuracy characterize the function of relative spectral luminous efficiency under different conditions of equivalent luminance adaptation [24, 25].

Figure 1. Variation of relative spectral luminous efficiency $V_{ek}(\lambda, L_{ek})$ at different luminous intensities of adaptation L_{ek}

Figure 2. Values of the coefficients $K_1(\lambda, L_{ek})$ and $K_2(\lambda, L_{ek})$ at $L_{ek} = 0.1 \text{ cd/m}^2$

Figure 3. Calculation of $K_2(\lambda, L_{ek})$

Table 1. Calculation of coefficients K_1 and K_2 for different equivalent luminance values

L_{ek} , cd/m ²	Coefficients obtained based on $V_{ek}(\lambda, L_{ek})$ CIE		Approximation results		Relative error of approximation, %	
	$K_1(L_{ek})$ CIE	$K_2(L_{ek})$ CIE	$K_1(L_{ek})$	$K_2(L_{ek})$	$K_1(L_{ek})$	$K_2(L_{ek})$
10 ⁻³	0.9486	0.0514	0.9486	0.0514	2,836·10 ⁻³	5,66·10 ⁻³
10 ⁻²	0.8471	0.1529	0.8471	0.1529	7,093·10 ⁻⁴	5,597·10 ⁻⁶
10 ⁻¹	0.4853	0.5147	0.4853	0.5147	5,072·10 ⁻⁵	4,783·10 ⁻⁵
1	0.1513	0.8487	0.1513	0.8487	2,745·10 ⁻⁴	4,893·10 ⁻⁵
10	0.0711	0.9289	0.0711	0.9289	3,375·10 ⁻⁴	2,584·10 ⁻⁵

Figure 4. Values of coefficients $K_1(L_{ek})$ and $K_2(L_{ek})$ **Figure 5.** Relative error of approximation $K_1(L_{ek})$ and $K_2(L_{ek})$

CONCLUSION

The theoretical study conducted has resulted into the following main conclusions:

- the use of the developed method enables to obtain results, which more accurately describe the efficiency of light sources in outdoor lighting installations compared to the results of the calculation according to standard methods;
- the calculation range $V_{ek}(\lambda, L_{ek})$ is increased by one order and reaches $10^{-3} \dots 10$ cd/m² by using 4 terms in the regression equation;
- it has been established that it is rational to present the function of spectral luminous efficiency for twilight vision as an approximation using two normalized functions of CIE: functions of spectral luminous efficiency for the night $V'(\lambda)$ and day $V(\lambda)$ vision.

The data provided in this paper may be useful to researchers and developers of lighting equipment, means and instruments for measuring and controlling photometric parameters of lighting installations of various purposes.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

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Зорове сприйняття в умовах зовнішнього освітлення

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Анотація. Світлодіодне вуличне освітлення є актуальним напрямком в сфері сучасного зовнішнього освітлення. Велика світлова віддача світлодіодів створює всі умови для модернізації існуючих мереж електроосвітлення в Україні. Зір людини – це складний процес, пов'язаний зі сприйняттям світла сітківкою ока. Зір поділяється на: денний, нічний і сутінковий. Робота ока істотно залежить від розподілу яскравості в полі зору. Спектральна чутливість фоторецепторів різна для різних довжин хвиль видимого спектру і різних рівнів інтенсивності світла. Нормування освітлювальної установки базується на детальних дослідженнях зорової працездатності спостерігача залежно від різних умов освітлення. Одним з основних світлових параметрів, який легко піддається об'єктивним вимірюванням, є освітленість. Яскравість, як функція освітленості, розташування спостерігача і спектрального коефіцієнта відбиття робочої поверхні більш інформативна, але має деякі труднощі при вимірюванні. Очевидна необхідність у розробці системи, що дозволяє однозначно оцінити зорову ефективність джерела світла заданого спектрального складу за певних умов спостереження. Вирішено в якості параметра такої системи ввести термін еквівалентної яскравості. Складність використання функції $V_{ek}(\lambda, L_{ek})$ для розрахунку еквівалентної яскравості полягає в залежності самої функції $V_{ek}(\lambda, L_{ek})$ від L_{ek} . Метою дослідження є апроксимація функції відносної спектральної світлової ефективності у мезопічній області набором стандартних функцій МКО, що не залежать від значення еквівалентної яскравості. Пропонується метод розрахунку $V_{ek}(\lambda, L_{ek})$ з використанням лише двох нормалізованих функцій відносної спектральної ефективності випромінювання для денного $V(\lambda)$ і нічного $V'(\lambda)$ зору. Використання такої функції апроксимації дає можливість за фотометричною яскравістю джерела світла визначити еквівалентну яскравість, яка адекватно відображає рівень зорового сприйняття в умовах зовнішнього освітлення. Для розрахунку $V_{ek}(\lambda, L_{ek})$ використовуються рекомендовані МКО функції відносної спектральної світлової ефективності для сутінкового зору, в основу яких покладено спектральний склад випромінювання чорного тіла з колірною температурою 2042 К. Використання розробленої методики дозволяє одержати результати, що точніше характеризують ефективність джерел світла в освітлювальних установках зовнішнього освітлення, ніж результати обчислення за стандартними методиками.

Ключові слова: світлодіодне освітлення, зорове сприйняття, світлова ефективність, еквівалентна яскравість.

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