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Investigation of Criteria for Comparing of Natural and LED Radiation Spectral Distribution

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Abstract

The difference in the spectral composition of artificial and natural lighting can negatively affect health, as well as lead to a distorted perception of the color of surrounding objects. At the same time, a certain correction of the spectral composition of visible radiation in medical institutions and workplaces has a positive effect on human health, while can be carried lighting control out taking into account the data of personal sensor devices that determine the human condition. The purpose of the research was to select criteria for comparing natural and LED optical and visible radiation by spectral composition and by the visibility of color differences in natural and LED lighting. The effectiveness of the application of known and developed criteria for assessing the difference in the spectral composition of optical and visible radiation from natural and LED sources was investigated, as well as for the visibility of color differences in natural and LED lighting. To minimize the values of criteria are proposed additive and subtractive methods for calculating LED parameters. Their comparison allowed us to conclude that a more complex calculation algorithm, but higher performance for an additive technique than for a subtractive one with the same minimization results.

It was found that to simulate the spectral composition of natural radiation using LEDs, it is most effective to use the criteria "standard deviations of the relative differences between the optical and visible spectral components of natural and LED radiation". A comparison of the criteria for the visibility of color differences in natural and LED lighting showed approximately the same effectiveness of using the criteria "small color differences" and "standard deviation by photoreceptors" at the present stage and the prospects for applying the second criterion, provided that its acceptable values are established.

Keywords: optical and visible radiation, natural and LED lighting, spectral composition, color differences, LED parameters

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Исследование критериев для сравнения естественного и светодиодного излучения по спектральному составу

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Различие в спектральном составе искусственного и естественного освещения может отрицательно сказаться на здоровье, а также привести к искажённому восприятию цвета окружающих предметов. В то же время определенная коррекция спектрального состава видимого излучения в медицинских учреждениях и на рабочих местах оказывает положительное влияние на здоровье человека, при этом управление освещением может осуществляться с учётом данных персональных сенсорных устройств, определяющих состояние человека. Целью исследований являлся выбор критериев для сравнения естественного и светодиодного оптического и видимого излучений по спектральному составу и по заметности цветовых отличий при естественном и светодиодном освещении. Исследовалась эффективность применения известных и разработанных критериев для оценки отличия спектрального состава оптического и видимого излучений от естественных и светодиодных источников, а также для заметности цветовых отличий при естественном и светодиодном освещении. Предложены аддитивная и субтрактивная методики расчёта параметров светодиодов для минимизации значений критериев. Их сравнение позволило сделать вывод о более сложном алгоритме расчёта, но большей производительности для аддитивной методики, чем для субтрактивной при одинаковых результатах минимизации. В результате исследований и проведенных расчётов установлено, что для имитации спектрального состава естественного излучения с использованием светодиодов наиболее эффективно использовать критерии «среднеквадратические отклонения относительных разностей оптических и видимых спектральных составляющих естественного и светодиодного излучения». Сравнение критериев заметности цветовых отличий при естественном и светодиодном освещении показало примерно одинаковую эффективность использования критериев «малые цветовые различия» и «среднеквадратическое отклонение по фоторецепторам» на современном этапе и перспективность применения второго критерия при условии установления его допустимых значений.

Ключевые слова: оптическое и видимое излучение, естественное и светодиодное освещение, спектральный состав, цветовые различия, параметры светодиодов

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Introduction

Currently, people use artificial lighting more than natural, the spectral composition of which depends on the geographical latitude of the area, time of day, time of year, weather conditions [1, 2]. Studies [3–8] have established that the difference in the spectral distribution of artificial and natural lighting can negatively affect health, as well as lead to a distorted perception of the color of surrounding objects. At the same time, a certain correction of the spectral composition of light radiation in medical institutions and workplaces has a positive effect on human health [9]. At the same time, lighting control can use the data of personal sensor devices that determine the human condition [10].

In addition to the effect on human health, the spectral composition of visible radiation determines the perception of the color gamut of reflective objects. The distribution of the spectral density of the radiation flux along the wavelength from objects is the product of the distribution of the spectral density of the radiation flux along the wavelength from the light source and the spectral distribution of the reflection coefficient of the object. This means that under different lighting conditions, the color of the same object may differ. The absence of color distortions can be important both in the production of technical products and in the visual assessment and perception of art objects.

From the above, it is obvious that it is possible to adjust the distribution of the spectral density of the radiation flux from artificial light sources in such a way that it is as close as possible to the distribution of the spectral density of the radiation flux from a natural source. If they coincide, the effect on the human body in general and on its visual system in particular will be the same. But due to the peculiarities of vision, it is possible that even if these distributions do not match, it is possible to ensure the so-called colorimetric accuracy, i.e. the invisibility of the difference between the color of the object and the color of the image [11].

The purpose of the research is to select criteria for comparing natural and LED optical and visible radiation in terms of spectral composition and the visibility of color differences. At the same time, it is necessary to solve 3 tasks: first, select the appropriate criteria, secondly, based on the proposed criteria, develop a methodology for calculating the parameters of LEDs that simulate natural lighting, and thirdly, evaluate the effectiveness of these criteria.

The ability to change the parameters of LED radiation

Currently, the most common sources of artificial indoor lighting are LEDs. The spectral density of the radiation flux of LEDs, with the exception of white ones, has a bell-shaped shape that does not cover the entire spectral range of natural radiation along the width of the base of the "bell". Therefore, to simulate the spectral composition of natural lighting, it is necessary to use different LED groups, each of which contains a certain number of LEDs with the same spectral radiation characteristics. At the same time, the characteristics of the various groups together should cover the entire spectral range of natural radiation. It is possible to adjust the spectral composition of the radiation generated by a set of groups, firstly, by changing the number of LEDs turned on within the group, and secondly, by changing the power supply current of the LED.

The spectral density of the radiation flux of the source $S_{e,\lambda}(\lambda)$ is calculated by the formula:

$$S_{e,\lambda} = \frac{dP_{e,\lambda}(\lambda)}{d\lambda},$$

where $P_{e,\lambda}$ is the radiation flux of the source.

According to [12], a change in current has a different effect the shape of the distribution of the spectral density of the optical radiation flux $S_{e,\lambda}(\lambda)$ for LEDs with different chemical bases. Red and yellow LEDs shift the wavelength of radiation corresponding with an increase in the supply current to the maximum intensity into the long-wavelength region of the spectrum. At the same time, the right branch of the "bell" expands, and the degree of these changes differs significantly for different types of red LEDs. For green LEDs, the corresponding shift and expansion occur in the opposite direction, into the short-wavelength region of the spectrum. For blue LEDs, the current change slightly affects the shape of the distribution of the spectral density of the optical radiation flux $S_{e,\lambda}(\lambda)$ and the displacement of its maximum. At the same time, the radiation power Peart of LEDs increases with an increase in the current passing through their structures [13, 14], and this dependence is linear:

$$P_{eart} = kP_{0eart}, \tag{1}$$

k is a parameter determined by the number m of emitting LEDs of one group and their supply current i, calculated by the formula:

$$P_{0eart} = \int_{\lambda\min}^{\lambda max} S_{0eart}(\lambda)d\lambda, \qquad (2)$$

where $\lambda_{\min}$, $\lambda_{\max}$ are the minimum and maximum wavelengths of the optical radiation range; the normalization condition has the form:

$$\int_{\lambda\min}^{\lambda\max} S_{0eart}(\lambda)d\lambda = 1. \qquad (3)$$

A comparison of equalities (1–3) shows that the dependence between the distribution of the spectral density of the optical radiation flux $S_{eart}(\lambda,k)$, created when m LEDs of the same group are switched on, through which current i flows, and the normalized distribution of the spectral density of their optical radiation flux $S_{0earn}(\lambda)$ is linear:

$$S_{eart}(\lambda,k) = kS_{0eart}(\lambda). \qquad (4)$$

If the lighting system includes LEDs of different spectral groups, then, taking into account expression (4), their total distribution of the spectral density of the optical radiation flux $S_{eart}(\lambda)$ calculated using the formula:

$$S_{eart}(\lambda) = \sum_{p=1}^{r} k_p S_{0eartp}(\lambda), \qquad (5)$$

where p is the number of a group of LEDs of the same type; r is the number of groups of LEDs of the same type; k_p is a parameter determined by the number of emitting LEDs of the same type m_p in the group and the relative value of the current supplying them i_p , calculated by the formula:

$$k_p = i_p m_p,$$

where i_p is the relative value of the current supplying the group of LEDs with the number p; m_p is the number of emitting LEDs in the group with the number p; $S_{0eartp}(\lambda)$ is the normalized distribution of the spectral density of the optical radiation flux for a group of LEDs with the number p, and the normalization condition is similar to condition (3):

$$\int_{\lambda\min}^{\lambda max} S_{0eartp}(\lambda)d\lambda = 1.$$

Criteria for distinguishing the spectral composition of natural and LED optical and visible radiation

In order to determine the parameters of artificial lighting, which ensure the minimum possible discrepancy between the distributions of the spectral density of the optical radiation flux of artificial and natural origin, it is necessary to select quantitative criteria for such a discrepancy. When choosing these criteria, it is possible to use the concept of physically accurate reproduction, designed to compare the reflection spectra of an object and its image. The classical definition of N.D. Nyberg's physical accuracy given in [15] implies that all corresponding points of the original and its image characterized by the same spectral composition of radiation perceived by the observer. With regard to the comparison of optical emissions, this definition interpreted as follows: the distribution of the spectral density of the optical radiation flux of a source is physically accurate with respect to the distribution of the spectral density of the optical radiation flux of another source, if these distributions coincide. Naturally, in this case, the observer will not notice the color change when replacing the light source.

Obviously, the simplest criterion for estimating the discrepancy between the two distributions of the spectral density of the optical radiation flux from natural $S_{enat}(\lambda)$ and artificial $S_{eart}(\lambda)$ sources is the standard deviation σ_e of their relative differences for all values of wavelengths λ, which must be minimized:

$$\min\sigma_e = \sqrt{\frac{\int_{\lambda_{\min}}^{\lambda_{\max}} \left(\frac{S_{enat}(\lambda) - S_{eart}(\lambda)}{S_{enat}(\lambda)}\right)^2 d\lambda}{\lambda_{\max} - \lambda_{\min}}}, \qquad (6)$$

where $S_{enat}(\lambda)$ and $S_{eart}(\lambda)$ are the intensity values, respectively; for natural and artificial radiation at the wavelength λ, $\lambda_{\min}$ and $\lambda_{\max}$ are the minimum and maximum values of the wavelengths of the visible radiation range.

In addition, it is possible to make a comparison not only for the distributions of the spectral density of the optical radiation flux $S_{enat}(\lambda)$ and $S_{eart}(\lambda)$, but also for the distributions of the spectral density of the visible radiation flux $S'_{nat}(\lambda)$ and $S'_{art}(\lambda)$, which can be calculated using the formulas:

$$S'_{nat}(\lambda) = S_{enat}(\lambda) \cdot V(\lambda); \qquad (7)$$

$$S'_{art}(\lambda) = S_{eart}(\lambda) \cdot V(\lambda), \qquad (8)$$

where $V(\lambda)$ is a function of the relative spectral luminous efficiency, for daytime vision it is given in accordance with GOST 8.332-2013[1].

[1] GOST 8.332-2013. The interstate standard. The state system of ensuring the uniformity of measurements. Light measurements. The values of the relative spectral luminous efficiency of monochromatic radiation for daytime vision. General provisions. The date of introduction is 2015-10-01. Edition (February 2019) as amended (IUS 7-2016).

In this case, the criterion is the standard deviation σ_v of the relative values for all components in the distributions of the spectral density of visible radiation fluxes, which also needs minimized:

$$\min\sigma_v = \sqrt{\frac{\int_{\lambda_{min}}^{\lambda_{max}} \left(\frac{S'_{nat}(\lambda) - S'_{art}(\lambda)}{S'_{nat}(\lambda)}\right)^2 d\lambda}{\lambda_{\max} - \lambda_{\min}}}. \quad (9)$$

In the first case (optical radiation), the effect of radiation on the human body as a whole is taken into account, taking into account the effect on ganglion cells that determine circadian rhythms, including sleep and wakefulness, in the second (visible radiation) – the effect only on its visual perception.

Information on the use of the standard deviation to compare the spectral flux densities of optical LED and natural radiation given in [16], and the spectral composition regulated by changing the number of LEDs of different groups.

By varying the number of LEDs of seven different groups with of 655 A total, it was possible to achieve a standard deviation of 21.4 % from the solar radiation spectrum. In addition, there was a significant unevenness in the sensitivity of ganglion cells (460 and 480 nm), which determine the regulation of circadian rhythms, and a decline in the long-wavelength region (670 nm).

Since the intensity of the LED radiation at any wavelength is directly proportional to the supply current. It is possible to minimize it by averaging over the number of identical LED groups the modulus of deviation of the maximum intensities in the distributions of the spectral density of the optical radiation flux for all groups of LEDs from the intensities of a similar distribution for a natural source at the corresponding wavelengths. So the criterion ΔA was selected the sum of the modules of the relative deviations of the maximum values of distributions $S_{eartp}(\lambda_{\max p})$ for each pth group of LEDs from the values of a similar distribution $S_{eartp}(\lambda_{\max p})$ for a natural source at the corresponding values of the wavelengths $\lambda_{\max p}$ of radiation. As in the case using the standard deviation σ, the calculation formulas of the second group of criteria ΔA_e and $\Delta A'$, respectively, for optical and visible radiation with a total number r of groups have the form:

$$\min\Delta A_e = \frac{1}{r}\sum_{p=1}^{r}\left|\frac{S_{enat}(\lambda_{\max p}) - S_{eartp}(\lambda_{\max p})}{S_{enat}(\lambda_{\max p})}\right|; \quad (10)$$

$$\min\Delta A' = \frac{1}{r}\sum_{p=1}^{r}\left|\frac{S'_{nat}(\lambda_{\max p}) - S'_{artp}(\lambda_{\max p})}{S'_{enat}(\lambda_{\max p})}\right|, \quad (11)$$

where $\lambda_{\max p}$ is the values of the radiation wavelengths corresponding to the maxima of the distributions of the spectral density of the radiation flux of LEDs in the p^{th} group, other designations correspond to those given earlier.

It should be noted that currently, for both variants of the criteria (σ_e, σ_v and ΔA_e, $\Delta A'$), there is no information about their acceptable values in terms of their effect on the human body in general and on the visual system in particular. Therefore, when analyzing the applicability of these criteria for evaluation, it is currently advisable guided by a comparison of their values and the nature of the discrepancies in the distributions of the spectral density of radiation fluxes of natural and artificial origin.

Criteria for the visibility of color differences in natural and LED lighting

To select criteria for the in distinguishability of the chromaticity of radiation from natural and artificial sources, the concept of physiologically accurate color reproduction used. If the colors of the image perceived by the observer as the same in relation to the colors of the object, according to N.D. Nyberg, physiologically accurate reproduction takes place [15]. R.W.G. Hunt [17] proposed the concept of "colorimetric accuracy of color reproduction", where an additional factor of physiological accuracy is the same conditions for viewing the original and reproduction, i.e. including the same spectral composition of lighting sources.

If the influence of visible radiation on color perception analyzed, then when choosing a criterion for comparing spectra from different sources, it is advisable to accept the condition of illumination of objects with the same spectral distribution of the reflection coefficient. Therefore, to analyze the color differences of radiation sources, a white background model chosen as a reflecting surface, in which the reflection spectrum is similar to that of the illuminate *CIE E* with a uniform relative distribution of radiation power over the spectrum, i. e. the reflection coefficient of the background surface in the entire visible range is constant.

Similarly to the comparison of the original and reproduction, in the future we will use the concept of "physiologically accurate reproduction" if the observer does not distinguish the color of the radiation from two sources on a white background with a constant reflection coefficient of the background surface in the entire visible range.

As a criterion for the difference between the chromaticity of natural and artificial radiation, we will consider the threshold ΔE of color difference, calculated from the distribution of the spectral density of optical radiation fluxes using color coordinates [18]. The threshold ΔE color difference defined as the difference between two colors in the CIELAB equidistant color space. This is the color space obtained by constructing in rectangular coordinates L^*, a^*, b^*, uniquely associated with the values of X, Y and Z of the three-color coordinates. Coordinate L^* characterizes the lightness proportional to the brightness and takes values from 0 (black) to 100 (white). Coordinate a^* characterizes the change in the hue of the color tone from green to red and vice versa, and coordinate b^* characterizes the change from blue to yellow and vice versa.

There are 4 known methods for calculating small color differences ΔE, developed by the International Commission on Lighting (ICO): 1950, 1976, 1994 and 2000. The formulas of the latest technique [19] contained mathematical gaps and implementation errors [20]. Therefore, the 1994 methodology used to calculate the ΔE threshold. According to this methodology:

$$\Delta E = \sqrt{\left(\frac{\Delta L}{k_L S_L}\right)^2 + \left(\frac{\Delta C}{k_C S_C}\right)^2 + \left(\frac{\Delta H}{k_H S_H}\right)^2}, \quad (12)$$

where ΔL, ΔC, ΔH are functions of the color coordinates L_{nat}^*, a_{nat}^*, b_{nat}^* of natural radiation and L_{art}^*, a_{art}^*, b_{art}^* of artificial radiation, the remaining coefficients are constants [18].

The coordinates L^*, a^*, b^* can be obtained based on the x, y, z coordinates of the color of the analyzed source, which, in turn, are functions of area-normalized fluxes of natural and artificial radiation, as well as addition curves for the color space of the 1931 MKO [18].

According to [21], small color differences ΔE are considered to be in the range from 1 to 10 units of color contrast, and if ΔE is less than 2.3 for two non-touching colors, then an ordinary observer hardly perceives this difference.

The development of another criterion for the visibility of color differences for natural and artificial lighting based on taking into account the direct effect on the photosensitive receptors of the visual analyzer. The effective energy effect $I_{B,G,R,Wnat}$ and $I_{B,G,R,Wart}$ for blue-, green- and red-sensitive photoreceptors and rods in color channels of the visual system determined as integral of the products of the spectral distributions $S_{enat}(\lambda)$, $S_{eart}(\lambda)$ of the natural or artificial radiation and of the spectral distribution of sensitivity $V_{B,G,R,W}$ [22, 23]:

$$I_{B,G,R,Wnat} = \int_{\lambda_{min}}^{\lambda_{max}} S_{enat}(\lambda) V_{B,G,R,W}(\lambda) d\lambda; \quad (13)$$

$$I_{B,G,R,Wart} = \int_{\lambda_{min}}^{\lambda_{max}} S_{eart}(\lambda) V_{B,G,R,W}(\lambda) d\lambda, \quad (14)$$

where $V_{B,G,R,W}$ are the spectral distributions of the sensitivities of each group of photoreceptors (B – red–sensitive, G – green–sensitive, R – red-sensitive cones, W – rods respectively) are calculated by the formula:

$$V_{B,G,R,W}(\lambda) = A_{B,G,R,W} V_{0B,G,R,W}(\lambda), \quad (15)$$

where $V_{0B,G,R,W}$ are the relative spectral distributions of the sensitivities of each group of photoreceptors, the maximum values of which are equal to 1; $A_{B,G,R,W}$ are the maximum values of the sensitivities of each group of photoreceptors, determined by weight coefficients, standard deviations and brightness of adaptation, given in [16].

In addition to cones and rods, the human visual analyzer contains photosensitive ganglion cells, which, according to recent studies [7], are not only associated with the effect on circadian rhythms, but also through the melanopsin produced by it can affect visual perception. This impact requires additional research and therefore cannot yet taken into account when developing the criterion.

In the presence of artificial lighting created by r groups of LEDs, the effect on each of the four photosensitive receptors, taking into account (13–15), described by the formula:

$$I_{B,G,R,Wart} = \int_{\lambda_{min}}^{\lambda_{max}} \sum_{p=1}^{r} S_{peart}(\lambda) A_{B,G,R,W} V_{0B,G,R,W}(\lambda) d\lambda. \quad (16)$$

It follows that if for each group of cones and for rods equality of integration results observed for two radiation sources, natural and artificial, the image will be physiologically accurate, i. e. the observer will not distinguish the color of the radiation sources even if their spectral distributions do not match.

Therefore, as a criterion, it is possible to use the standard deviation ε of the relative differences $\varepsilon_{B,G,R,W}$ of the effects of natural and artificial radiation on blue-, green- and red-sensitive photoreceptors, as well as rods:

$$\min\varepsilon = \sqrt{\sum_{B,G,R,W} \varepsilon^2_{B,G,R,W}}, \quad (17)$$

where:

$$\varepsilon_{B,G,R,W} = \frac{I_{B,G,R,Wnat} - I_{B,G,R,Wart}}{I_{B,G,R,Wnat}}, \quad (18)$$

values of $I_{B,G,R,Wnat}$ and $I_{B,G,R,Wart}$ are calculated using formulas (13) and (16), respectively.

In the future, we will call the criterion the standard deviation of ε for photoreceptors. There is currently no information on the acceptable values of the ε criterion.

A method for determining the parameters of LED lighting to simulate the spectral distribution of natural radiation

To optimize LED lighting that mimics natural lighting, it is necessary to perform 2 steps. First, you need to select the necessary set of LED groups containing LEDs with the same spectral characteristics. Secondly, it is necessary to calculate the relative values of currents in each group of LEDs, which minimize the discrepancy in the distributions of the spectral density of radiation fluxes from LED and natural sources in accordance with the criterion used. At the same time, the condition of normalization (equality 1) of the area under the total distribution of the spectral density of radiation fluxes for LED and natural sources must observed.

It is possible to use both additive and subtractive variants to perform the calculation.

In the additive version, the minimum number of LED groups selected, the combination of which provides coverage of the entire spectral range. Next, using the *gamultiobj* function, which is a genetic optimization algorithm for the MatLab application software package, optimization performed based on two criteria's: by minimizing the analyzed criterion and by the condition of equality of 1 area under the total spectral distribution (normalization condition). The criterion is calculated for all possible combinations of k_p parameters (formula (5)). A combination of them is selected in which the deviation of the area from 1 is no more than 1 % and the value of the criterion is minimal. At the same time, it assumed that a change in the current in the LED does not lead to a change in the wavelength corresponding to the maximum radiation. Formulas (3), (6), (9)–(12), (17) used for the calculation. If the emission spectra of natural and calculated artificial sources do not match, their difference calculated, representing a set of graphs of spectral sensitivity graphs of the missing LED groups in the set. After calculating the difference, the previously selected set of groups manually or automatically supplemented with groups of LEDs with spectral characteristics corresponding to the groups missing in the difference, and the calculation performed again. Then the above cycle repeated until the values of the criterion and the discrepancy in the distribution graphs of the spectral density of radiation fluxes for LED and natural sources become acceptable.

In the subtractive version, the maximum possible number of LED groups selected from the LED catalogues; the second stage performed similarly. When calculating, some groups of LEDs turn out to be superfluous due to the zero value of the corresponding parameter k_p.

When using an additive technique, the volume of calculations increases from cycle to cycle, an analysis of the results after each cycle is required and the introduction of spectral density distributions of radiation fluxes for new groups of LEDs, carried out by the user or automatically. These two operations complicate the algorithm in relation to the subtractive technique. In this case, the user can stop the calculation at any stage that satisfies him according to the results. The subtractive technique provides for a single introduction of spectral characteristics of a large number of different LED groups, one long calculation cycle, and the absence of the possibility of user intervention before the end of the cycle. The considerable duration of the calculation cycle when using a subtractive technique compared with an additive one can become an obstacle in its use if it is necessary to reconfigure LED lighting quickly in accordance with rapidly changing natural lighting.

In order to test the developed programs, 3 cycles of calculations using the additive method carried out for all the criteria considered in this paper and the calculation for criterion σ_v using the subtractive method. At the same time, the calculation duration using the subtractive method with the introduction of spectral characteristics of 31 LED groups as initial data exceeded the calculation duration of one cycle using the additive method by about 58 times.

The normalized by area spectral distribution of daylight power at a correlated color temperature (CCT) of 10000 K [7] as natural radiation is used:

$$\int_{\lambda\min}^{\lambda\max} S_{nat}(\lambda)d\lambda = 1.$$

As part of the first cycle of calculations using the additive method, 4 groups of LEDs were selected (blue QB-12, green ZG-10, red SY-28, yellow SE-28) [24], the spectral characteristics of which covered the wavelength range of radiation from about 415 to 670 nm. At the second stage, in addition to the above four groups, a fifth was introduced, containing a warm white LED with two phosphors with a CCT of 2700 K with a spectral range width of 400–800 nm [25]. After the second cycle, based on the calculated difference in the spectral density distributions of natural and artificial radiation fluxes, additional groups from the commercially available list used in [21] were added to the already existing LED groups, and a third calculation cycle was carried out. The spectral characteristics numbers of the added groups from the list shown in Table 1 for each criterion.

As an example, Figure 1 shows graphs of spectral density distributions of optical LED radiation fluxes obtained of each of the three calculation cycles while minimizing the criterion "relative standard deviation σe of the values of spectral density distributions of optical radiation flux".

Table 1

The numbers of spectral characteristics from the list of groups used in [21], added at the third stage

Designation of the criterion	Spectral characteristics numbers of the added groups
σ_e	6, 9, 19, 26
σ_v	11, 18, 19
ΔA_e	6, 9, 11, 20
$\Delta A'$	1, 9, 11, 18
ΔE	2, 6, 12, 18, 20
ε	6, 11, 19

The analysis of the graphs presented in Figure 1 shows that, with the transition to each subsequent cycle corresponding to an increase in the number of LED groups, the discrepancy between the spectral density distributions of optical LED and natural radiation fluxes decreases.

The values of all six minimized criteria obtained of each calculation cycle are presented in Table 2 as a result, and the results of calculating the k_p parameter values for each group of LEDs after the third cycle are shown in Table 3. k_p values in Table 3 are arranged in the following order: first for groups containing LEDs QB-12, ZG-10, SY-28, SE-28, then for a group of warm white LEDs with two phosphors, then for the added groups according to the numbers from Table 1.

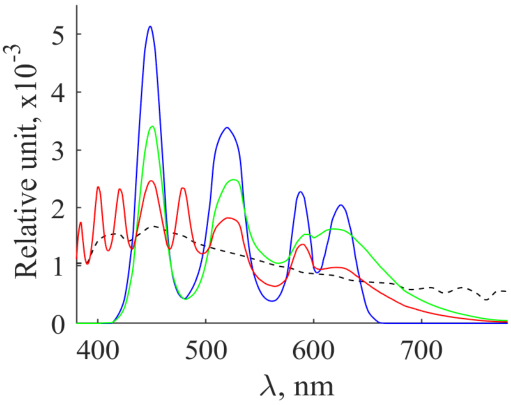

Figure 1 – Graphs of the distribution of the spectral density of the optical radiation flux from a natural source at a CT of 10000 K (dotted line) and the results of three cycles of calculating similar distributions from an LED source for the criterion σ_e (blue line – after the first cycle, green – after the second, red – after the third)

The data in Table 2 indicate that after each calculation cycle, the values of all criteria decrease. At the same time, different combinations of k_p parameter values for LED groups correspond to each criterion, which is shown in Table 3 as an example.

The spectral characteristics of 29 commercially available LEDs were additionally introduced into the initial data for calculation using the subtractive method the available list used in [21] in addition to the spectral characteristics of the groups used in the second cycle of additive calculation (blue QB-12, green ZG-10, red SY-28, yellow SE-28 [24] and warm white LED [25]).

Table 2

The values of the minimized criteria after each calculation cycle

Cycle number	The values of the minimized criteria					
	σ_e	σ_v	ΔA_e	$\Delta A'$	ΔE	ε
1	1.0173	0.60779	0.91746	0.35289	8.526	0.5862
2	0.49051	0.33778	0.69179	0.185043	8.4913	0.35472
3	0.30334	0.2883	0.45468	0.096771	1.342	0.28557

Table 3

K_P parameter values for each LED group after the third calculation cycle

Designation of the criterion	k_p									
σ_e	0.0072	0.1531	0.1372	0.0436	0.3149	0.1238	0.0953	0.0828	0.0425	
σ_v	0.0000	0.1556	0.0160	0.0160	0.5806	0.1132	0.0581	0.0578		
ΔA_e	0.0178	0.3115	0.2203	0.0128	0.0589	0.0261	0.0282	0.1640	0.1474	
$\Delta A'$	0.0138	0.1175	0.0149	0.0092	0.1502	0.0066	0.0071	0.5813	0.0965	
ΔE	0.0293	0.0776	0.0559	0.0363	0.0557	0.2144	0.0693	0.0573	0.1669	0.2338
ε	0.2528	0.0677	0.1684	0.0138	0.1142	0.1488	0.0304	0.1998		

Approximately equal values of criterion σ_v (0.2883 and 0.29483) were obtained by additive after 3 calculation cycles and subtractive methods as a result of minimizing this criterion. The corresponding graphs of the spectral density distributions of optical radiation fluxes practically coincided in both cases. In the first case, 9 LED groups were used for the synthesis of artificial radiation, in the second – 13.

Analysis of the effectiveness of the criteria for distinguishing the spectral composition of natural and artificial radiation sources

A comparison of the results of minimizing the criteria "standard deviation" σ_e, σ_v and the criteria "average sum of the deviation modules of the maximum intensity values in the radiation spectrum of the LED groups" ΔA_e and $\Delta A'$, respectively for light and visible radiation, showed that the first pair of criteria is preferable according to calculations and graphs. The cycle calculation time for both groups of criteria turned out to be approximately the same. The simplification of the calculation algorithm by replacing the integral over the entire spectrum in the first case of radiation with the sum of the maximum intensity values in the radiation spectrum of LED groups of LED groups in the second offset by the need to introduce these maximum values into the algorithm. Besides the graphs of the LED of spectral density distributions of fluxes for the criteria of the group "standard deviation σ_e" demonstrated a greater and consistent approximation to the distribution of the natural radiation spectrum after each calculation cycle than for the criteria "average sum of the modulus of deviations for optical radiation spectrum of the LED groups ΔA_e". The same result was obtained when analyzing the criteria σ_v and $\Delta A'$ for visible radiation. As examples, Figure 2 shows, respectively, graphs of the spectral density distributions of LED optical radiation fluxes obtained as a result of the third calculation cycle according to the criteria σe and ΔA_e, and Figure 3 shows graphs of the corresponding spectral density distributions of LED visible radiation fluxes according to the criteria σ_v and $\Delta A'$.

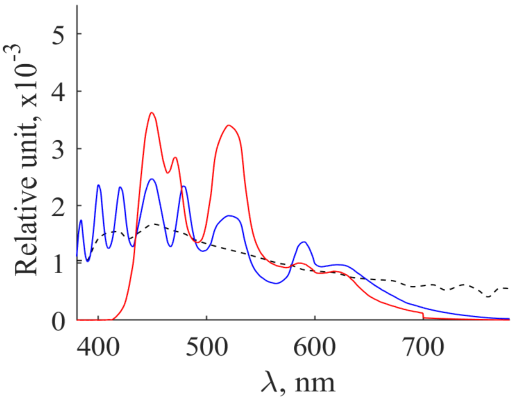

Figure 2 – Graphs of the distribution of the spectral density of the optical radiation flux from a natural source at a CT of 10000 K (dotted line) and the results of the third cycle of calculation of similar distributions from an LED source (blue line – calculation according to the criterion σ_e, red – calculation according to the criterion ΔA_e)

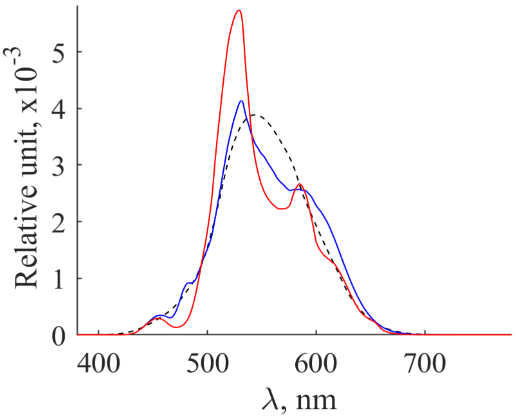

Figure 3 – Graphs of the distribution of the spectral density of the visible radiation flux from a natural source at a CT of 10000 K (dotted line) and the results of the third cycle of calculation of similar distributions from an LED source (blue line – calculation according to the criterion σ_v, red – calculation according to the criterion $\Delta A'$)

Analysis of the effectiveness of the criteria for the visibility of color differences in natural and artificial lighting

A study of the effectiveness of criteria evaluating the visibility of color differences in different lighting showed that, in addition to the traditionally used criterion of small color differences Δ*E*, it is possible to use the criterion "standard deviation ε by photoreceptors". This criterion represents the standard deviation of the relative differences in the effects of natural and artificial radiation on blue-, green- and red-sensitive photoreceptors, as well as rods. After each calculation cycle for both criteria, the value of the criteria decreased (Table 2), and for criterion ε – with greater monotony. The value of Δ*E* after the third calculation cycle corresponded to the invisibility of color differences when illuminating a white sample with selected natural and artificial radiation [21]. At the same time, the discrepancies in the distribution graphs of the spectral density of visible radiation fluxes for natural and LED sources were smaller when calculated using the criterion ε (Figure 4).

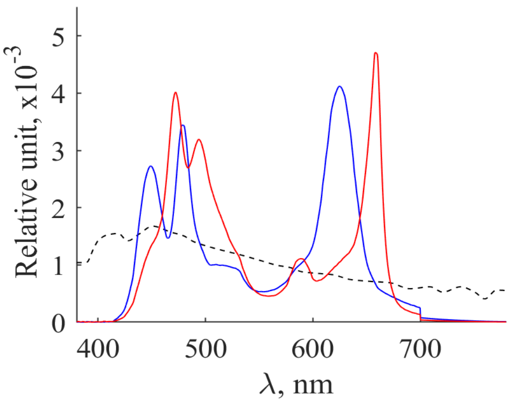

Figure 4 – Graphs of the distribution of the spectral density of the optical radiation flux from a natural source at a CCT of 10000 K (dotted line) and the results of the third cycle of calculating similar distributions from an LED source for the criterion "standard deviation ε by photoreceptors" (blue line) and the criterion "small color differences Δ*E*"(red)

Each of these two criteria has its advantages and disadvantages. For the Δ*E* criterion, despite cumbersome calculations using empirical coefficients and there are known as mathematical gaps and implementation errors [20] in the 2000 version, the acceptable values given, in particular, in [21]. Acceptable values for the ε criterion are not currently set. They can be determined by comparing them with the values of Δ*E* under the same lighting conditions.

The acceptable values for the ε criterion are not currently established. They can be determined by comparison with the values of Δ*E* under the same lighting conditions. At the same time, it can be entered the values of the coefficients determining the photosensitivity of the photoreceptors of the visual analyzer at different brightness adaptations into the calculation. In addition, the method of calculating the criterion ε is simple. The values of the energy are used absorbed by photoreceptors, so a criterion ε has a physical meaning. After conducting experiments to determine the acceptable values of the criterion, its use may become more preferable.

Conclusion

To compare the spectral composition of natural and LED energy and light emissions, 2 groups of criteria were selected. These include, firstly, the standard deviations of the relative differences in the spectral density distributions of their optical and light radiation fluxes of natural and LED radiation, and secondly, the averaged modules of deviation of the maximum amplitudes of LED radiation from the amplitudes of natural energy and light radiation at the corresponding wavelengths. To assess the visibility of color differences in natural and artificial lighting, the following were used: the well-known criterion of small color differences and the developed criterion "standard deviation by photoreceptors", which takes into account the effects of radiation on blue, green and red-sensitive photoreceptors, as well as rods.

A comparison of subtractive and additive methods for calculating the parameters of LEDs that minimize the criteria allowed us to conclude that the calculation algorithm is more complex, but its performance is higher for the additive method than for the subtractive one with the same minimization results.

The criteria "relative standard deviations of the values of the spectral density distributions of the optical and light radiation flux for LED and natural sources" are more effective than the criteria associated with averaged modules of deviation of the maximum intensity of LED radiation from the intensity of natural radiation to simulate the spectral composition of natural radiation.

A comparison of the criteria for the visibility of color differences showed their approximately equal efficiency of use at the present stage, as well as the prospects of using the criterion "standard deviation by photoreceptors" if it's acceptable values are established.

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