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NON-VISUAL EFFECTS OF LIGHT AND THEIR SIGNIFICANCE IN LED LIGHTING SYSTEMS DESIGNING: A CRITICAL REVIEW OF THE INTEGRATED LIGHTING PROBLEM

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Introduction. In addition to ensuring the human visual function, visible light has non-visual biological and psychological effects. The non-visual effects of light affect a human's health, well-being, activity and sleep. Comfortable lighting that harmoniously combines both visual and non-visual effects and creates physiological and psychological benefits for people is defined as "integrated lighting". Modern standards for artificial lighting focus only on visual effects, visual comfort and energy efficiency and do not refer to the non-visual impact of light on humans. Recently, a number of national and industry standards have been developed, as well as expert proposals, which provide recommendations regarding the regulation of parameters of integrated lighting systems, but these documents have not been agreed upon in accordance with an accredited standards development process.

The aim of this research – to analyze the methods of assessing the non-visual impact of light on humans and the recommendations of experts regarding the standardization of integrated lighting parameters, as well as the development of proposals for improving national regulatory documents on electric lighting in Ukraine, taking into account the visual and non-visual effects of light.

Materials and methods of the research. An analytical review of scientific publications over the past 30 years was performed using the databases EuroPub (Great Britain), Science Direct – Scopus – Web of Science – Core – Google Scholar "Google Academies", Hinari Access to Research for Health, National Library of Medicine, U.S. Environmental Protection Agency, National Library of Ukraine named after V. I. Vernadskyi, Budstandart, as well as scientific publications taken from open sources.

Results. The purpose of integrated lighting is to provide optimal illuminance according to human needs, taking into account the visual and non-visual effects of light by adjusting its intensity and color in different periods of the day. Current international standards regarding interior lighting are based only on visual characteristics, measures to ensure visual comfort and energy efficiency. Currently, there are no international standards setting requirements for integrated lighting. None of the international standardization bodies, including CIE and IES, have yet approved the proposed integrated lighting parameters and metrics for evaluating the circadian efficiency of artificial light sources. There are two main approaches to quantifying the circadian efficiency of lighting: metric of equivalent melanopic lux, based on the melanopic light response of photoreceptors (ipRGC) with a maximum at 490 nm; the circadian stimulus (CS) metric is developed based on the spectral sensitivity of all photoreceptors based on circadian phototransduction studies. A circadian stimulus quantifies the circadian efficacy of light measured as suppression of melatonin secretion after 1 h of nocturnal illumination. The main methods of increasing the circadian efficiency of lighting systems are increasing the level of vertical illumination and increasing the share of short-wavelength light in the source spectrum.

Conclusions. Daylight is the most effective for stimulating the circadian system and reduces the use of electrical energy for artificial lighting, so increasing the use of daylight is an important direction for improving the efficiency of integrated lighting. When designing integrated lighting, such factors as a person's age, health, work mode, diet, sleep, and others should be taken into account. On the basis of the conducted analysis, for the application of integrated lighting in Ukraine, it is recommended to make changes to the DBN for internal lighting of workplaces and living spaces only for daytime activity of people. The level of vertical illumination is recommended to be set in accordance with the recommendations of the WELL building standard regarding the design of circadian lighting.

Ключові слова: light, photoreceptors, non-visual effects, melanopic equivalent of daylight, led lighting systems, integrated lighting

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Introduction

Since the 2000s, the attention of physicians, biologists, ecologists, and lighting engineers has been drawn to the problems of non-visual effects of light on the human body and its consequences for health. The emergence of this problem is connected with the opening of the non-visual channel of light perception by ganglion cells of the retina, the signals from which are sent directly to the pineal gland – a neuroendocrine organ that regulates the secretion of the hormone melatonin. The action of the biological channel consists in the fact that intense lighting inhibits the secretion of melatonin and causes a state of activity in the body, and a low level of illumination promotes the secretion of this hormone, which leads to relaxation of the body and sleep. Such synchronization of the state of the human body with the surrounding light environment has evolutionary roots. Life on Earth developed in accordance with the natural cycle of day and night. Most organisms, including humans, have developed circadian oscillators precisely tuned to changing light levels, and their physiology and behavior are controlled by this cycle. In 2002, a variety of photoreceptors was discovered – photosensitive ganglion cells (ipRGC), which are connected to the suprachiasmatic nuclei (SCN), which form a structure in the brain that acts as the main biological clock [1]. In the absence of natural rhythms of light and darkness, the change of which is caused by the rotation of the Earth, the biological clock can lose phase, which will have negative consequences for health.

Today, the concept of good lighting goes beyond the requirements for ensuring visual functions. Medical and biological studies have shown that light, in addition to the visual function, causes a non-visual biological and psychological effect on humans, which is called the non-imaging forming (NIF) response or non-visual (NV) reaction. The non-visual effects of light affect a person's health, well-being, activity and even sleep [2]. Good lighting also involves the absence of light at a certain time of the day. Lighting that combines both visual and non-visual effects and creates physiological and/or psychological benefits for people is called integrated lighting [3]. It is also called circadian or biodynamic lighting, as well as human-centered lighting, but these are marketing terms according to the CIE position. Integrated lighting is the official term for lighting that is designed to integrate visual and non-visual effects, creating physiological and psychological effects on people that are reflected in scientific evidence [4].

Modern standards for artificial lighting focus only on visual aspects, visual comfort and energy efficiency and do not concern the non-visual impact of light on a person. Photometric and colorimetric parameters used to describe, design and measure the parameters of internal lighting systems include the level and uniformity of illumination, the brightness of lamps, ceilings, walls, glare limitations, the spatial distribution of light intensity, the color of light and the quality of color rendering, as well as indicators of brightness flickering, stroboscopic effect and photobiological safety of light. However, until now there are no international standards and recommendations regarding the normalization of non-visual parameters of biological action and metrics of circadian characteristics of light.

The spectral sensitivity of ipRGC ganglion cells, which contain the photo-pigment melanopsin, differs from the spectral sensitivity of rods and cones. Rods and cones have a neural connection with ganglion cells and their signals interact with the signals of ganglion cells. The nature of these interactions is not fully understood, which is why the functions of the spectral sensitivity of the non-visual effects of light are not defined. The function of spectral sensitivity of ganglion cells is standardized by CIE [5]. In the future, when developing recommendations regarding the assessment of non-visual effects of light, the CIE also suggests using a standard D65 light source with a correlated color temperature (CCT) 6500 K [6].

Recently, a number of national and industry standards have been developed, as well as expert proposals, which provide recommendations regarding the standardization of parameters of integrated lighting systems and the establishment of their threshold values, but these documents have not been agreed in accordance with the accredited process of developing standards and have not yet been recognized in the established order by authoritative international standardization organizations. Research related to the non-visual impact of light on a person and the design of integrated lighting systems continues and is extremely relevant today.

The aim of this research – is to analyze the methods of assessing the non-visual impact of light on humans and the recommendations of experts regarding the standardization of integrated lighting parameters, as well as the development of proposals

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for improving national regulatory documents on electric lighting in Ukraine, taking into account the visual and non-visual effects of light.

Materials and methods of the research

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Results of the research and their discussion

Review of Research Methods and Indicators

The main problem in the design of lighting systems taking into account the non-visual effect of light is the lack of officially recognized international standards regarding metrics of circadian characteristics of light and requirements for integrated lighting [7]. Today, there are two approaches to creating circadian photometry:

- on the basis of one photoreceptor (ganglion cells of the retina) proposed [8];
- based on all five photoreceptors (retinal ganglion cells, rods and three types of cones) proposed in [9].

The method for evaluating the circadian efficiency of light proposed in [8] is based on experimental data on inhibition of melatonin secretion by light with different wavelengths, obtained by the authors of the studies [10, 11]. Figure 1 shows the spectral dependence of inhibition of melatonin secretion by light. The photoreceptor, which is responsible for suppressing melatonin secretion, has maximum sensitivity at a wavelength of 460 nm. However, in studies [12], where white light of different colors (warm white and cold white) was used instead of monochromatic, it was shown that the response curve of suppression of melatonin secretion has an additional maximum with a wavelength between 470 and 510 nm. The dotted curve in Figure 1 has a trend that cannot be explained by the sensitivity of a single photoreceptor. It was hypothesized that rods and cones, which have a neural connection with ganglion cells and their signals interact with signals coming from the ganglion cells themselves, can also participate in the suppression of melatonin secretion. The solid curve (Figure 1) proposed in [13] emphasizes the negative effect of light with a wavelength above 550 nm on suppression of melatonin secretion. Blue light alone is more effective at suppressing melatonin secretion than white light with higher energy, consisting of blue and yellow components. The most important aspect of this principle is that the photosensitivity of the circadian system does not exhibit

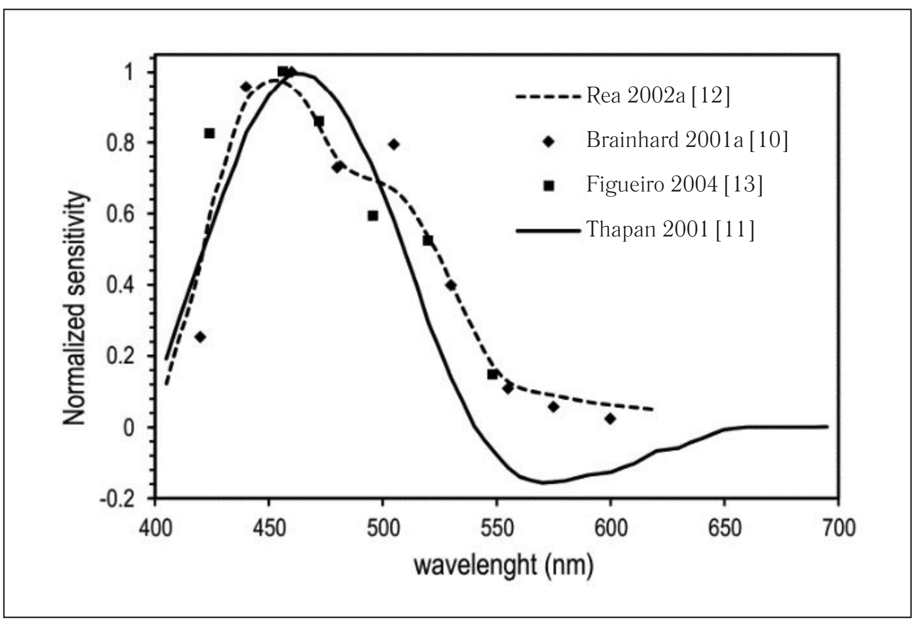

Figure 1. Action spectra of melatonin secretion inhibition

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additive behavior with respect to light of different wavelengths when considered separately, but becomes more sensitive to blue light as yellow-red light decreases. The hypothesis about the spectral opposition of circadian sensitivity, which is also confirmed in the study [14], suggests that ipRGC ganglion cells also receive information from retinal bipolar cells. Many of these neural connections are still unknown, making it impossible to define a single spectral sensitivity function or action spectrum for all non-visual light exposures [15].

In [8] determination of circadian values is carried out with the help of photometric values, using the function of spectral sensitivity of suppression of melatonin secretion $c(\lambda)$ (Figure 1) obtained on the basis of research in [10, 11].

Using the circadian sensitivity function $c(\lambda)$ and the spectral distribution of light energy $X_{e\lambda}$, it is possible to calculate the energy circadian characteristics of light X_{ec} [8]:

$$X_{ec} = \int X_{e\lambda}\, c(\lambda)\, d\lambda \qquad (1)$$

The ratio of integrals of circadian and photometric characteristics is called the circadian efficiency coefficient a_{cv}:

$$a_{cv} = \frac{\int X_{e\lambda}\, c(\lambda)\, \mathrm{d}\lambda}{\int X_{e\lambda}\, v(\lambda)\, \mathrm{d}\lambda}, \qquad (2)$$

where $v(\lambda)$ is a function of the relative spectral efficiency of daytime vision.

As a first approximation, a_{cv} can be determined from the CIE chromaticity coordinates:

$$a_{cv} \approx \frac{\int X_{e\lambda}\, \bar{z}(\lambda)\, \mathrm{d}\lambda}{\int X_{e\lambda}\, v(\lambda)\, \mathrm{d}\lambda} = \frac{z}{y} = \frac{1-x-y}{y} \qquad (3)$$

where x, y, z are color coordinates.

The circadian efficiency factor a_{cv} allows you to calculate the circadian integral value of light from the equivalent photometric value. Table 1 shows a_{cv} for typical light sources; the a_{cv} ratio increases almost linearly with an increase in CST.

Table 2 shows the relationship between human activity, a_{cv} coefficient, and correlated color temperature [6].

Table 1

Value of a_{cv} for different sources of light

Sources of light	CCT, K	a_{cv}, relat. units	Sources of light	CCT, K	a_{cv}, relat. units
Direct rays of the Sun	5081	0.76	White LEDs	2800	0.37
Blue sky	19963	1.49		4200	0.71
Cloudy sky	5924	0.88		6300	1.02
Fluorescent lamps	2827	0.31	Blue LED with λ = 468 nm		6.9
	6678	0.52	Incandescent lamp	2800	0.35
	6500	0.94	High pressure sodium lamp	2770	0.28

Table 2

Relationship between human activity, coefficient a_{cv}, ratio, and correlated color temperature (CCT)

Type of human activity	a_{cv}	CCT, K
Moments of peace, relaxation	< 0,4	< 3300
Types of lighting: office, industrial, street, commercial and educational institutions	0.3–0.8	3300–5300
Optimum concentration at work with high visual loads	> 0.7	> 5300

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The hypothesis using one receptor has a number of limitations: the time factor of circadian light exposure is missing; the circadian sensitivity function $c(\lambda)$ does not take into account the contribution of other photoreceptors to ipRGC signals and does not take into account the unevenness of the function between 470 and 510 nm. Because of this, this model using a single receptor overestimates the circadian effect of light sources with CST > 4000 K. This method is easy to apply and is used for approximate estimates of the circadian efficiency of light.

Another metric based on a single photoreceptor, which relies on the melanopsin spectral sensitivity curve with a maximum at 490 nm, called the equivalent melanopic lux (EML) method, proposed in [17]. It also does not take into account the contribution of other photoreceptors (cones and rods) that carry information to the ipRGC. The melanopic response curve is slightly different from the values obtained in the studies [10, 11].

The equivalent melanopic lux is calculated as:

$$EML = E \cdot R, \tag{4}$$

where, E is the photopic illuminance measured at eye level in lux, R – the melanopic efficiency of light in relation to melatonin inhibition, which varies between 0.45 and 1.70 units [18].

The *EML* technique helps differentiate light sources that create the same visual effect. For example, incandescent lamps producing 200 lux have 108 *EML*, while daylight at 200 lux has 220 *EML*.

It should be noted that the *EML* metric does not correspond to the International System of Units (SI), so the International Commission on Illumination (IEC) introduced a modified form of the *EML* metric. The CIE standard [5] recommends instead of *EML* the melanopic equivalent of daylight (mel.EDI), expressed in lux. The relationship between *EML* and mel.EDI is as follows:

$$EML = \text{mel.EDI} \cdot 1.103. \tag{5}$$

Daylight melanopic equivalent mel.EDI is based on standard light (D65) as a reference source and shows daylight illumination that provides the same melanopic illumination effect as the test source. For example, mel.EDI 150 lux means that the evaluated light source creates the same illumination that suppresses melatonin secretion as 150 lux of daylight at SST 6500 K. In the study [19], the recommended mel.EDI during the day should be at least 150 lux, at night the maximum value of mel.EDI should be 10 lux. mel.EDI is calculated by multiplying the photopic illuminance (E) by the melanopic daylight efficiency ratio (mel.DER), which varies from 0.40 to 1.60 units [18].

A later model of circadian photometry was proposed in [9] using all five receptors. The spectral sensitivity of these photoreceptors is shown in Figure 2.

The concept of spectral melanopic sensitivity was introduced in the standard [5]. Five spectrally weighted irradiances received the general name "alpha – opic irradiance", each of which is named after its own pigment: melanopic (ipRGC), rod or rhodopic (r-type), cyanopic (s-type cones), chloropic (cones m-type) and erytropic (l-type cones).

The method for quantifying the effectiveness of non-visual stimulation is developed on the basis of the spectral response of photopigments and photoreceptors and is based on neurophysiology and neuroanatomy research on circadian phototransduction [21]. Phototransduction is the process by which ganglion cells convert light energy into nerve signals. The CS circadian stimulus metric quantifies the efficacy of light on the circadian system, measured as suppression of melatonin secretion after 1 h of nighttime illumination (at 2.3 mm pupil diameter). According to this model, the maximum suppression of melatonin secretion after 1 h of light is 0.7 units, whereas 0.3 units in the morning is sufficient to promote circadian stimulation. The CS value expresses the percentage of suppression of melatonin secretion, varying from 0 to 70%. The CS model involves first determining the circadian illuminance (CL_A), where CL_A is the spectrally weighted irradiance at the level of the retina, which depends on the spectral sensitivity function of ipRGC, rods and cones [9].

Measurements are carried out using the Daysimeter device [22]. To determine the CS based on the CL_A circadian light, the equation is used [23]

$$CS = 0.7 - \frac{0.7}{1 + \left(\frac{CL_A}{355.7}\right)^{1.1026}} \tag{6}$$

For CL_A and CS calculations, you can use the CS calculator [24], it provides CL_A and CS values for different light sources and can calculate CS values from the given light spectra [25].

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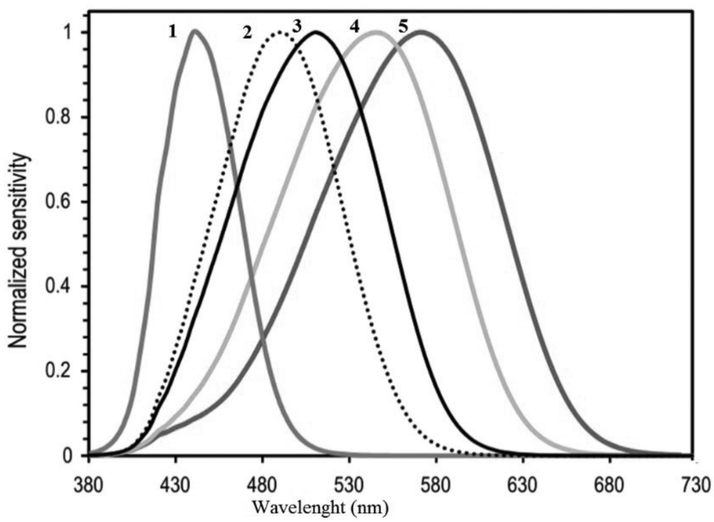

Figure 2. Spectral sensitivity of photoreceptors recommended by CIE TN 003:2015 [20]:

1. ssc (λ) – spectral sensitivity of cones containing cyanopsin, with maximum sensitivity at 440 nm;
2. sz (λ) is the spectral sensitivity of ipRGCs containing melanopsin, with a sensitivity maximum at 490 nm;
3. sr (λ) is the spectral sensitivity of rods containing rhodopsin, with maximum sensitivity between 505 and 510 nm;
4. smc (λ) – spectral sensitivity of cones containing chloropsin, with maximum sensitivity at 545 nm;
5. slc (λ) is the spectral sensitivity of cones containing erythropsin, with maximum sensitivity at 570 nm

The metric [9] is non-linear to interpret the unevenness of the circadian sensitivity function between 470 and 510 nm. At the same time, the effect of the spectral opposition of the signal of blue-yellow colors, which affect the ipRGC signals, is taken into account. The threshold level (minimum effect) and saturation level (maximum effect) for suppression of melatonin secretion is determined depending on the amount of light falling on the retina. Using this model, the equivalent circadian light (CL_A) is calculated, which is defined as the radiation flux per unit area after 1 hour of its exposure. This is a dimensionless value that can be compared with the concept of illumination. On the basis of CL_A, it is possible to calculate the circadian stimulus (CS), which is a dimensionless value from 0.1 to 0.7 units, which is proportional to the rate of nocturnal melatonin suppression in humans. It should be noted that the CS metric also has limitations: it concerns temporal aspects such as the duration of illumination, time of day, history of previo us exposure to light on people.

The recommended input is the spectral illuminance of the eyes, but this method does not take into account the modification of the spectrum reaching the eyes due to the reflectance of surfaces in the environment.

One of the factors that must be taken into account when designing circadian lighting is the phase shift of melatonin secretion as a result of the influence of night lighting. It has been experimentally established that even moderate artificial lighting in the late evening can significantly change the cycle of melatonin secretion and its amount during the day, while the dependence of "light dose – melatonin secretion shift response" is not linear [26]. Thus, an illumination level of 500 lux creates a delay of approximately 2.5 hours, and 100 lux – for 1.5 hours.

The classical model of sleep is based on the interaction of two different processes:

- the process of homeostasis, which is characterized by an increase and decrease in pressure after waking up and during sleep, respectively;
- the circadian process, which provides a "sleep window".

Light and darkness at the appropriate time affect the sleep process and this must be taken into account when designing circadian lighting systems. Yesterday's daylight affects last night's sleep, and both the level of illumination and the spectrum of light play a role here. Light affects sleepiness and activity in two different ways (Figure 3).

Way 1 begins in the daylight hours of the previous day and affects the quality of sleep at night, which in

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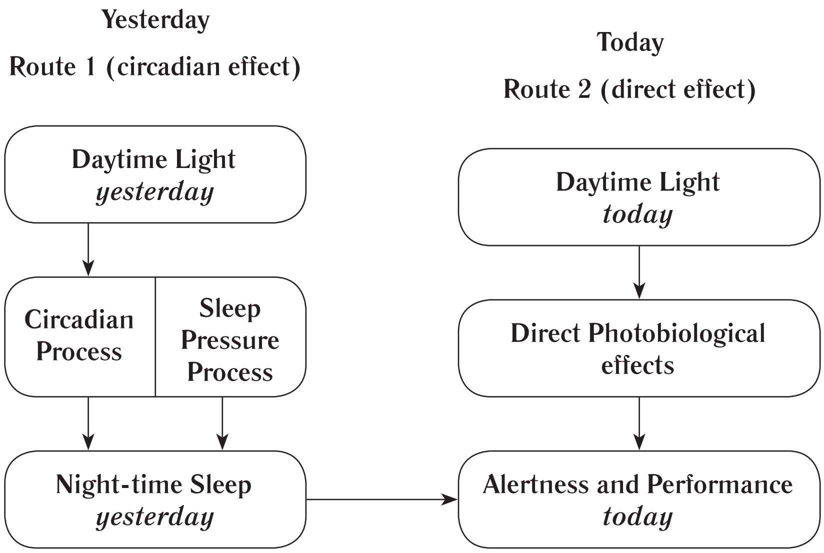

Figure 3. Two ways in which daylight can affect daytime alertness and performance [15]

turn affects sleepiness, activity, and performance today.

Way 2 — direct photobiological influence of light, which causes an activating effect during the illumination process [15].

In addition to the considered problems, there are still a number of difficulties related to the design of circadian lighting systems, in particular, the correct assessment of the spectrum of lighting that reaches the human eye and its spatial distribution, taking into account the influence of the environment, individual characteristics of people, physical exertion, etc.

Review of Integrated Lighting Features

In this section, an analysis of some features of integrated lighting, recommendations for establishing requirements for integrated lighting in separate industry standards, as well as proposals for improving national regulatory documents for artificial lighting in Ukraine were carried out.

Since circadian rhythmicity is a property of almost every physiological, metabolic and behavioral system¸ this phenomenon puts a wide range of biological processes under the indirect control of the retina. Light constricts the pupil, inhibits melatonin secretion, increases heart rate and body temperature, stimulates cortisol production, and acts as a neurophysiological stimulant. Lighting time can be used as a therapy for circadian rhythm sleep disorders and circadian rhythm associated with shift work and changing time zones.

It should be noted that there are no universal approaches when designing integrated lighting. People who are active during the day benefit from light with high biological activity in the morning and afternoon, low efficiency in the evening and least at night. People who are active at night need adequate lighting to safely perform professional tasks at night, while minimizing the potential negative effects associated with wakefulness and nighttime lighting. For nocturnal workers, visual and non-visual needs conflict, requiring prioritization. Many people who work at night perform critical functions (for example, doctors, nurses, pilots, dispatchers, etc.). For them, factors such as visibility and attention take priority over circadian synchronization, even if disruption of the circadian rhythm is associated with negative health consequences.

Recommendations for the design of integrated lighting based on industry standards and recommendations of experts are given in studies [18, 27] (Table 3). Design criteria for integrated lighting are based on the temporal structure of light exposure (time of day, duration of exposure), illuminance levels, spectral distribution of radiation power, and spatial distribution of light. These factors influence the biological effectiveness of the light stimulus and can be manipulated to affect two categories of human responses to light — visual and non-visual. In the study [16], it is recommended that artificial lighting imitates the dynamics of natural lighting, changing its intensity and color throughout the day. But the

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imitation of daylight can never be completely achieved due to the large difference between the radiation spectrum and intensity of daylight and artificial light. The level of lighting created by daylight is approximately 10–50 times higher than the created by artificial light sources according to modern standards. Due to the fact that in order to achieve the limit level of the circadian stimulus CS greater than ⩾ 0.3, it is necessary to spend more global energy than is established by the standard EN 12464-1 [28]. The research [29] shows that the required level of illuminance of the cornea of the eye to achieve CS ⩾ 0.35 for daylight D65 is 233 lux, for a fluorescent lamp with CCT 4000 K – 575 lux, for a lamp with CCT 5000 K – 387 lux, for lamps with CCT 6430 K – 266 lux. The vertical illuminance in the premises according to the requirements of the standard [28] is significantly less than these values. Artificial lighting can provide a sufficient level of E_V illuminance by increasing the power of lighting systems or increasing the CCT [30]. Using light sources with a CCT of 8000 K to achieve CS ⩾ 0.35, illuminance E_V 187 lux is required. To achieve the recommended values of circadian efficiency, higher levels of illuminance are required than those set for visual functions by the standard [28], which negatively affects the energy efficiency of lighting [31]. In this regard, when using integrated lighting, the problem of minimizing electricity consumption becomes relevant. Our evaluations show that only the use of light-emitting diode (LED) light sources with their functionality and potential to increase energy efficiency can provide energy consumption indicators that do not exceed current requirements for ensuring human visual functions. LED technologies and automatic control systems make it possible to move from lamps with fixed color and light intensity to dynamic lighting systems with adjustable color and light parameters. With the help of LEDs, it is possible to provide a CST range of light in the range of 2300–8000 K. The role of LEDs in creating integrated lighting is crucial for reducing electricity consumption. In [27], it is recommended to use lamps that direct the light upwards, and the ceiling and walls have high light reflection coefficients to increase the vertical illuminance "E_V". In order to minimize the optical power of lighting systems to ensure the necessary vertical illumination during the day, it is necessary to use light sources with higher circadian efficiency coefficients and to use natural light as much as possible.

The total illumination of the cornea consists of direct illumination that comes directly from the light source, and indirect illumination that is created due to the reflection of light before it reaches the eye. The desired ratio of direct and indirect lighting is different for visual and non-visual effects. From the point of view of energy efficiency of lighting for visual tasks, the component of direct light should be higher than the reflected light, while for non-visual impact, on the contrary, the component of reflected light should be higher. The recommended ratio of vertical and horizontal illuminance to obtain CS ⩾ 0.3 should be $E_V/E_N \geqslant 0.65$ [27].

To ensure high values of vertical illumination, light reflection coefficients and the color of the internal surfaces of the room (walls, ceiling) play an important role. The study [32] investigated the influence of color and light reflection coefficients of interior surfaces of rooms on potential visual and non-visual lighting parameters. The results showed that the light reflection coefficient affects both the brightness level and the color change of reflective surfaces. Matte surfaces increase the ratio of melanopic brightness to photopic and SST compared to glossy surfaces. Reflective surfaces of dark colors negatively affect the circadian efficiency of rooms, white surfaces can provide more than 50% more effective biological stimulation compared to colored surfaces (yellow, orange) [32]. Incorrect choice of interior surface colors can reduce circadian stimulation despite good performance in terms of visual requirements. Improving the reflection of internal surfaces is a simple and cheap way to increase indirect illumination of the cornea of the eye [30]. Directing the initial light flux upwards (to the ceiling) leads to a more uniform and higher level of indirect illumination of the cornea of the eyes. One of the ways to increase the level of vertical illumination, as recommended in [31], is the additional use of local lighting (table lamps).

One of the ways to create new highly efficient integrated lighting systems is to use international, national and industry standards of different countries. The standards reflect advanced scientific and technical experience, contribute to streamlining the processes of development, manufacture and testing of products. Standards are developed on the principle that they should be based on new knowledge and state-of-the-art and are the result of collaboration

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Table 3

Circadian lighting parameters are recommended by regulatory documents and experts

Normative documents, source of information	Measurement unit	Quantitative lighting parameters	Time of exposure
DIN SPEC 67600:2013-04 [34]	Photopic lux	$E_V \geqslant 250$ лк, CCT = 8000 K; $E_V \geqslant 290$ лк, CCT = 6500 K;	A few hours during a day
		$E_V \leqslant 50$ лк, CCT $\leqslant$ 2700 K	In evening before going to bed
Circadian lighting design [35]	*EML*, relat. Units	*Work places:* $E_V \geqslant 200$ *ЕМЛ* (daylight and electric lighting) $E_V \geqslant 150$ *EML* (electric lighting) *Household conditions:* $E_V \geqslant 200$ *EML*, $E_V \leqslant 50$ *EML*	From 9 to 13 hours During the day At night
Recommendations for healthy indoor day and night lighting [19]	mel.EDI, lux	$E_V \geqslant 250$ $E_V \leqslant 10$ $E_V \leqslant 1$	During the day 3 hours before bedtime During sleep
Instructions for designing circadian lighting [36]	Circadian CS stimulus, relat. Units	CS $\geqslant$ 0.3 CS $\leqslant$ 0.2 CS $\leqslant$ 0.1	$\geqslant$ 2 hours per day (7:00 a.m. to 4:00 p. m.) At evening At night

between industry, science, occupational health and safety, and a range of stakeholders. The development of international standards, even if the principles of development are followed, is a too long process, so industry or national standards are often used. For example, DIN SPEC standards can be developed in a few months. They do not conflict with any existing standards and can be used as a basis for a full standard. The SPEC modifier means that the standard was not developed as part of the full consensus standardization process established by ISO. Using such standards is the fastest way to implement a project from research to implementation [33]. Table 3 shows some parameters of industry standards and recommendations of experts regarding integrated lighting.

In Ukraine, the use of integrated lighting can be started following the example of some countries by developing a standard for integrated lighting or making changes to the current national standards for lighting, in particular, changes to the State Building Regulations. At the first stage, these changes may concern only the spheres of workplace lighting with daytime activity of people. The simplest recommendation for this category is to provide light of high biological efficiency during the day and low at night. The lighting parameters can be set in accordance with the WELL standard [35], the positive results from the use of integrated lighting according to the recommendations of which have been numerically confirmed. In the standard [35] developed by the International Institute of Construction, the levels of illuminance at workplaces, which should not be lower than 200 *EML*, are defined. Residential premises should also be lit at a level of at least 200 *EML* during the day and no more than 50 *EML* at night (in the period 2 hours before going to bed and before waking up).

It should be noted that the DBN V.2.5-28:2018 [37] also needs to make a number of changes related to the visual effects of light, which are important for integrated lighting. In particular, this refers to the

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evaluation of the discomfort glare of LED light sources using the generalized discomfort indicator UGR according to CIE 117-19-95 [38]. As a number of studies have shown, this indicator is ineffective for evaluating LED lamps with uneven brightness [15]. In SIE 232-2019 [39] introduced temporary changes in the methodology for determining UGR, which will be in effect until practical results are obtained using a fundamental approach based on physiological and psychological mechanisms.

It is also necessary to make changes regarding the new requirements for parameters of blinking and stroboscopic effect of LED light sources and methods of their measurement, established by EU Commission Regulation No. 2019/2020 [40].

As for workplaces with nocturnal activity of people, individual approaches are needed to ensure the appropriate level of illumination and spectrum at the right time of the day for the right period. When designing integrated lighting, such factors as a person's age, state of health, work mode, sleep, etc. should be taken into account.

Lighting for the elderly is also one of the priority areas of application of integrated lighting [41]. Aging is associated with physiological and psychological changes that disrupt the body's reaction to light (yellowing of lens pigmentation, reduction in the diameter of the pupil of the eye). A 20-year-old person receives three times more light than a 60-year-old person. This reduces sensitivity to world signals and makes older people more vulnerable to the effects of lighting, their cognitive performance and sleep quality.

Integrated lighting systems consume more energy than classic systems to provide only visual needs, but further studies have shown that automatic LED lighting control systems and the use of daylight not only have a positive effect on the energy balance, but also on the health and satisfaction of consumer needs. With this in mind, integrated lighting systems must be designed to take into account the use of daylight and automatic control of LED lighting.

Conclusions

1. The purpose of integrated lighting is to provide optimal illuminance according to human needs, taking into account the visual and non-visual effects of light by adjusting its intensity and color temperature in different periods of the day.
2. Current international standards regarding interior lighting are based only on visual characteristics, measures to ensure visual comfort and energy efficiency.
3. Currently, there are no international standards setting requirements for integrated lighting. None of the international standardization bodies, including CIE and IES, have yet approved the proposed integrated lighting parameters and metrics for evaluating the circadian efficiency of artificial light sources.
4. There are two main approaches to quantifying the circadian efficiency of lighting:
   - metric of equivalent melanopic lux, based on the melanopic light response of photoreceptors (ipRGC) with a maximum at 490 nm;
   - the CS circadian stimulus metric is developed based on the spectral sensitivity of all photoreceptors based on circadian phototransduction studies.

   A circadian CS stimulus quantifies the circadian efficacy of light measured as suppression of melatonin secretion after 1 h of nocturnal illumination. The CS value expresses the percentage of suppression of melatonin secretion, varying from 0 to 70%.
5. The main methods of increasing the circadian efficiency of lighting systems are increasing the level of vertical illumination and increasing the share of short-wavelength light in the spectrum of the source.
6. Daylight is the most effective for stimulating the circadian system and reduces the use of electrical energy for artificial lighting, so increasing the use of daylight is an important direction for improving the efficiency of integrated lighting.
7. When designing integrated lighting, such factors as a person's age, health, work mode, diet, sleep, and others should be taken into account.
8. On the basis of the conducted analysis for the application of integrated lighting in Ukraine, it is recommended to make changes to the DBN for internal lighting of workplaces and living spaces only for daytime activity of people. The level of vertical illumination is recommended to be set in accordance with the recommendations of the WELL building standard regarding the circadian lighting design of inner premises.

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НЕВІЗУАЛЬНІ ЕФЕКТИ СВІТЛА ТА УРАХУВАННЯ ЇХ У ПРОЕКТУВАННІ СИСТЕМ СВІТЛОДІОДНОГО ОСВІТЛЕННЯ: ОГЛЯД ЛІТЕРАТУРИ ЩОДО ПРОБЛЕМИ ІНТЕГРОВАНОГО ОСВІТЛЕННЯ

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Вступ. Окрім забезпечення зорової функції людини, видиме світло має незоровий біологічний і психологічний вплив. Незорові ефекти світла впливають на здоров'я, благополуччя, активність і сон людини. Комфортне освітлення, що гармонійно поєднує як візуальні, так і не візуальні ефекти та створює фізіологічні та психологічні переваги для людини, визначають як «інтегроване освітлення». Сучасні стандарти щодо штучного освітлення зосереджені тільки на візуальних ефектах, зоровому комфорті й енергоефективності та не стосуються невізуального впливу світла на людину. Натепер розроблено ряд національних і галузевих стандартів, а також пропозицій експертів, в яких надаються рекомендації стосовно нормування параметрів систем інтегрованого освітлення, але ці документи не були узгоджені відповідно до акредитованого процесу розроблення стандартів і поки не визнані в установленому порядку.

Мета дослідження – порівняльний аналіз стандартизованих методів оцінювання невізуального впливу світла на людину та рекомендацій експертів щодо нормування параметрів інтегрованого освітлення, а також розроблення пропозицій стосовно вдосконалення національних нормативних документів на штучне освітлення в Україні з урахуванням візуального та невізуального впливів світла.

Матеріали та методи дослідження. Аналітичний огляд наукових публікацій за останні 30 років виконано з використанням баз даних EuroPub (Велика Британія), Science Direct – Scopus – Web of Science – Core – Google Scholar «Академії Google» Hinari Access to Research for Health, National Library of Medicine, U.S. Environmental Protection Agency, БУДСТАНДАРТ Online, наукові публікації з відкритих джерел.

Результати. Мета інтегрованого освітлення – забезпечити оптимальне освітлення відповідно до потреб людини з врахуванням візуальних і невізуальних ефектів світла шляхом регулювання його інтенсивності та колірності в різні періоди доби. Чинні міжнародні стандарти стосовно внутрішнього освітлення базуються лише на візуальних характеристиках, заходах із забезпечення зорового комфорту й енергоефективності. Натепер відсутні міжнародні стандарти, що встановлюють вимоги до інтегрованого освітлення. Жоден із міжнародних органів зі стандартизації, зокрема CIE та IEC поки що не схвалив запропоновані параметри інтегрованого освітлення та метрики для оцінювання циркадної ефективності штучних джерел світла. Існує два основних підходи до кількісної оцінки циркадної ефективності освітлення:

– метрика еквівалентного меланопічного люкса, що базується на меланопічній відповіді на світло фоторецепторів (ipRGC) із максимумом при 490 нм;
– метрика циркадного стимулу (CS), яка розроблена на основі спектральної чутливості всіх фоторецепторів, що базуються на дослідженнях циркадної фототрансдукції. Циркадний стимул кількісно визначає циркадну ефективність світла, яку виміряно як пригнічення секреції мелатоніну після 1 год нічного освітлення. Основними методами підвищення циркадної ефективності систем освітлення є збільшення рівня вертикальної освітленості та частки короткохвильового світла в спектрі джерела.

Висновки. Денне світло є найефективнішим для стимулювання циркадної системи та зменшує використання електричної енергії на штучне освітлення, тому збільшення використання денного світла є важливим напрямом підвищення ефективності інтегрованого освітлення. При проєктуванні інтегрованого освітлення мають бути враховані наступні фактори: вік людини, здоров'я, режим роботи, дієта, сон та інші. На основі проведеного аналізу для застосування інтегрованого освітлення в Україні рекомендується внести зміни в ДБН для внутрішнього освітлення робочих місць і житлових приміщень тільки для денної активності людини. Рівень вертикальної

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освітленості рекомендується встановити відповідно до рекомендацій будівельного стандарту WELL щодо дизайну циркадного освітлення.

Ключові слова: світлове забруднення, світлодіодні джерела освітлення, циркадні ритми, спектр випромінювання, яскравість, освітленість, фотобіологічна небезпека світла

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