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Effect of the illuminance meter used on the results of color light pollution measurements

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***Abstract*—The paper presents the results of measurements of illuminance. Twenty-two types of illuminance meter with known spectral sensitivity curves of photometric heads and eleven lamps emitting colored light were used. Laboratory measurements were conducted at a characteristic point, with a focus on assessing intrusive light, with a value of 3 lx. The considerations were supplemented with simulated illuminance calculations. For most illuminance meters, correlations were observed between the measurement results and the calculations. This allows the conclusion that, especially in the case of colored light, one of the main factors affecting the measurement result is the spectral sensitivity curve of the photometric head. The greatest discrepancies in the obtained illuminance values were found in the case of lamps emitting blue light. The paper highlights the fact that measuring low illuminance values produced by lamps emitting colored light is not an easy task. Depending on the illuminance meter used, conclusions regarding the assessment of intrusive light may vary. The aim of the paper is to indicate that not all calibrated illuminance meters are suitable for this assessment.**

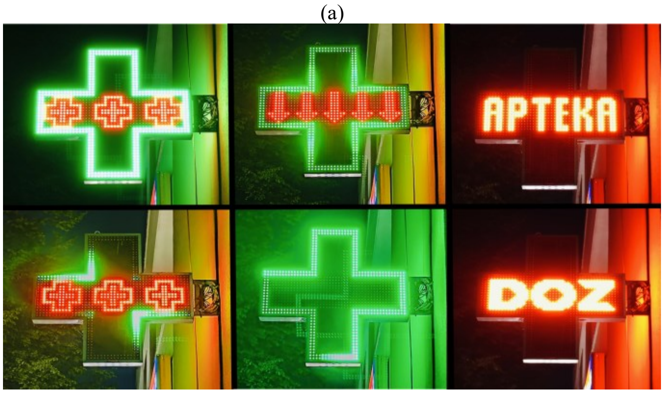
***Keywords*—illuminance meter; illuminance measurements; colored light; spectral sensitive curve; illuminated advertising**

I. Introduction

ONE way to attract the attention of potential customers and distinguish a brand from its competition is through illuminated advertisements. Illuminated advertising often serves as a key marketing tool and a form of communication with the customer. The aim of such advertising can be to encourage the use of services, to make a purchase, or to promote the brand. Illuminated advertisements also serve an informational function, indicating, for example, the location of a company's headquarters or its opening hours.

One of the significant stimuli that capture human attention and reinforce the message is the color of light. Therefore, colored light sources play an important role in advertising. In the 20th century, advertisements using neon tubes (known as neon signs) were very popular, followed by low-pressure fluorescent lamps. Currently, LED technology dominates. The major advantages of LED technology include high luminance (which significantly impacts the visibility of the advertisement), energy efficiency, long lifespan, the ability to produce different light colors, and extensive control options (which are used in advertisements displaying variable content). These advantages have made the advertising industry one of the sectors that quickly adopted LED technology. Figure 1 shows sample images of illuminated advertisements made using LED technology. They utilize LEDs emitting colored light. The first advertisement (Figure 1a) is in the form of a sign, with LEDs arranged along the contours of the letters forming the inscription. The second advertisement is in the shape of a cross, inside which there is an LED matrix. It displays variable content, graphics, and animations (Figure 1b).

(a)



(b)

Fig. 1. Photos of sample illuminated advertisements using LED technology (a) static advertising, (b) dynamic advertising

It is worth mentioning that colored light is also used in the illumination of architectural objects, as noted in the literature [1]. In the case of light emissions from illuminated advertisements located in residential areas, we can refer to it as intrusive light. Illuminated advertisements (especially those using LED technology) are characterized by high emission parameter values. The light emitted by advertisements often illuminates the facades of neighboring residential buildings. It

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penetrates through windows into the interiors of rooms, causing them to be lit at night. Excessive light emission can cause discomfort for residents, create feelings of inconvenience, or be a source of health problems. Artificial light at night (ALAN) can pose a risk of lifestyle diseases [2]. According to extensive literature, the most detrimental effect of artificial light at night on humans is the reduction in melatonin secretion [3], which can lead to: shortened sleep duration [4], the presence of depressive symptoms [5], increased incidence of obesity [6], cardiovascular diseases [7], and type II diabetes [8]. To mitigate the nuisance caused by light emitted by external lighting equipment, legal regulations have been introduced to specify the maximum allowable illuminance values on the facade of a building. This parameter (illuminance) is used for the quantitative assessment of external light.

II. Research Problem

In Poland, guidelines for limiting intrusive light are included in the Regulation of the Minister of Infrastructure of April 15, 2022, on the technical conditions to be met by buildings and their location [9]. According to the provision contained in this legal act: lighting devices, including illuminated advertisements placed outside or near a building, must not cause inconvenience to its users. If the light from illuminated advertisements is directed at the facade of a building containing windows, the illuminance on that facade must not exceed 5 lx for white light and 3 lx for colored light or light with varying intensity. It is worth noting that the cited legal act does not specify any requirements for measuring instruments used to verify the compliance of lighting conditions with the requirements of this regulation.

To assess the level of intrusive light, one can perform simulation calculations using computer programs that support the design of electric lighting [10] or conduct field measurements. It is worth mentioning that conducting computer simulations requires knowledge of the photometric data of the lighting equipment (one needs to have photometric files, e.g., in IES or LDT format [11]). While such data is usually available for luminaires, it is not typically provided for illuminated advertisements. Additionally, it should be noted that computer programs used for lighting design do not consider spectral characteristics in the calculation process, as pointed out in the literature [12]. The primary measuring instrument used in field measurements of intrusive light is an illuminance meter (lux meter). One of the most important components of a illuminance meter is the photometric head. A key issue in the construction of photometric heads is adjusting the spectral sensitivity of the photocell or other type of transducer to the spectral sensitivity of the human eye. Since the sensitivity curves of individuals are not identical (depending on individual human characteristics), the International Commission on Illumination (CIE) has adopted standardized values of the relative spectral luminous efficiency V(λ) for daylight vision [13]. Under these conditions, the human eye shows maximum sensitivity at a wavelength of 555 nm. An ideal observer, whose relative spectral sensitivity curve aligns with V(λ) for daylight vision, is called the CIE standard photometric observer. In practice, the sensitivity curves of the photometric heads of illuminance meters differ (to a greater or lesser extent) from the V(λ) curve. This affects the measurement results, as noted in the literature [14]. Previous measurements published in studies [14], [15] using various types of illuminance meters referred to white light. Given that the assessment of illuminance threshold values can also pertain to colored light, the research question is: how does the quality of the measuring instrument (illuminance meter) affect the assessment of intrusive light?

The issue of the impact of colored light on measurement results was highlighted in the study [16]. For 10 illuminance meters, whose spectral sensitivity curves were obtained from data provided by the manufacturers, spectral correction factors were calculated. However, laboratory measurements were conducted using only 3 illuminance meters, utilizing lamps emitting white light.

The issue discussed by the authors is important from a metrological point of view. This arises from two factors. Firstly, photometric laboratories use luminous intensity standards, which are typically incandescent lamps, when calibrating illuminance meters. The spectral characteristics of colored light differ significantly from the spectral characteristics of radiation emitted by an incandescent lamp. Consequently, there may be large discrepancies in the results obtained from measurements made at the same point but with different illuminance meters. The reason for this may be the low quality of the components used to implement spectral corrections in the photometric heads of some illuminance meters. It is worth emphasizing that the calibration certificate of a illuminance meter does not provide information on the influence of the spectral distribution of radiation emitted by different types of light sources on the indications of a given illuminance meter, as pointed out in [17]. This means that errors during measurements of illumination intensity produced by colored light can be significantly larger than errors determined during the calibration of illumination intensity meters. Another problem is the measurement of low illumination intensity values. At relatively low levels of illumination intensity, many factors can influence the measurement result. Factors such as ambient temperature, device resolution, battery charge level, meter operating mode (continuous, maximum, integration), dark current of the photometric detector, imperfect spectral and spatial matching of the photometric head, may have a greater impact on the measurement result when small values are measured.

III. Subject, Scope and Method of the Study

A. *Subject of study*

Twenty-two illuminance meters were subjected to the study. The selected photometers represent a sample of illuminance meters available on the market. The actual spectral sensitivity curves of the photometric heads of each illuminance meter are shown in Figure 2. The sensitivity curves are the result of measurements conducted in the Calibration and Research Laboratory for Optical Radiation (CARLO) [18].

Additionally, on the same graph, the V(λ) sensitivity curve is included, filled with yellow color. This allows deviations in the sensitivity of the photometric heads from the required V(λ) curve for individual wavelengths in the visible range to be observed. The measure of the mismatch between the actual spectral sensitivity of the photometric head and the reference sensitivity V(λ) is the spectral mismatch error [19], denoted by the symbol f_1'. The values of the f_1' error for each photometer are provided in the legend. For the purposes of this study, arbitrary numbering from 01 to 22 was assigned to each illuminance meter, ranked according to the f_1' value (from smallest to largest).

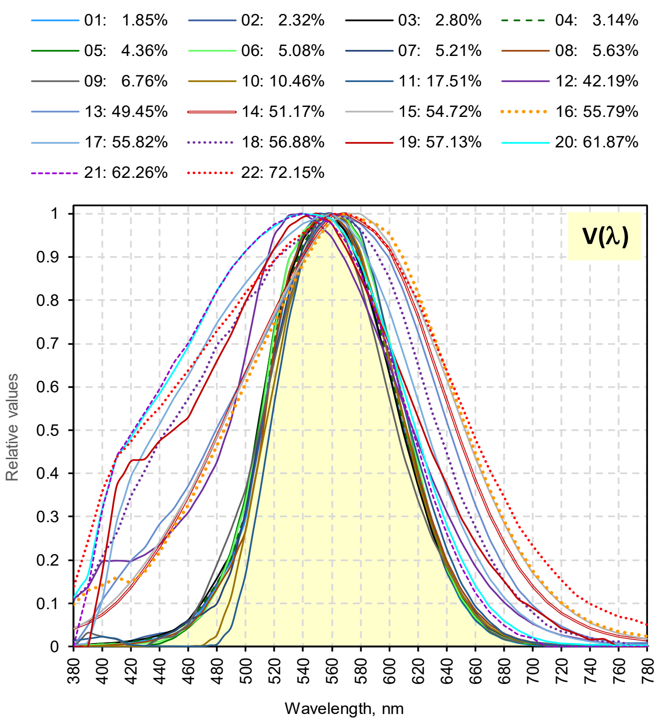


Fig. 2. The actual spectral sensitivity curves of the photometric heads of the illuminance meters along with the reference sensitivity curve V(λ)

B. *Scope of research*

The scope of the study included measuring illuminance at a characteristic point of 3 lx. In the considerations, an incandescent lamp (representing Illuminant A) and 11 colored light sources were used, which are potentially used or may be used in advertising lighting. Four LED sources were considered, emitting light in the following colors: blue, green, orange, and red. The radiation of monochromatic diodes is characterized by a spectral distribution, often close to a normal distribution, with a maximum at a specific wavelength. There is a wide range of colored LED sources. However, due to the time required for the study, only a few typical (most popular) colors were considered (see Fig. 3a).

A relatively new solution is LED filament lamps, where individual LED sources are mounted on a glass substrate, resembling a traditional bulb. Hence, the colloquial name for these sources: LED Filament. In the study, four such lamps were used in the following colors: blue, green, orange, and red. The spectral characteristics of these lamps are shown in Fig. 3b.

The study also included three low-pressure fluorescent lamps in three typical (most commonly encountered on the market) light colors: blue, green, and red. Despite the fact that these lamps cannot be introduced to the European Union market as of August 25, 2023 [20], due to their interesting spectral characteristics, it was decided to include them in the considerations (see Fig. 3c).

For those with a single peak, the full width at half maximum $\Delta\lambda_{1/2}$ of the radiation emitted by the lamp is indicated. This is the distance between points on the curve where the values on the spectral characteristic reach half of the maximum value.

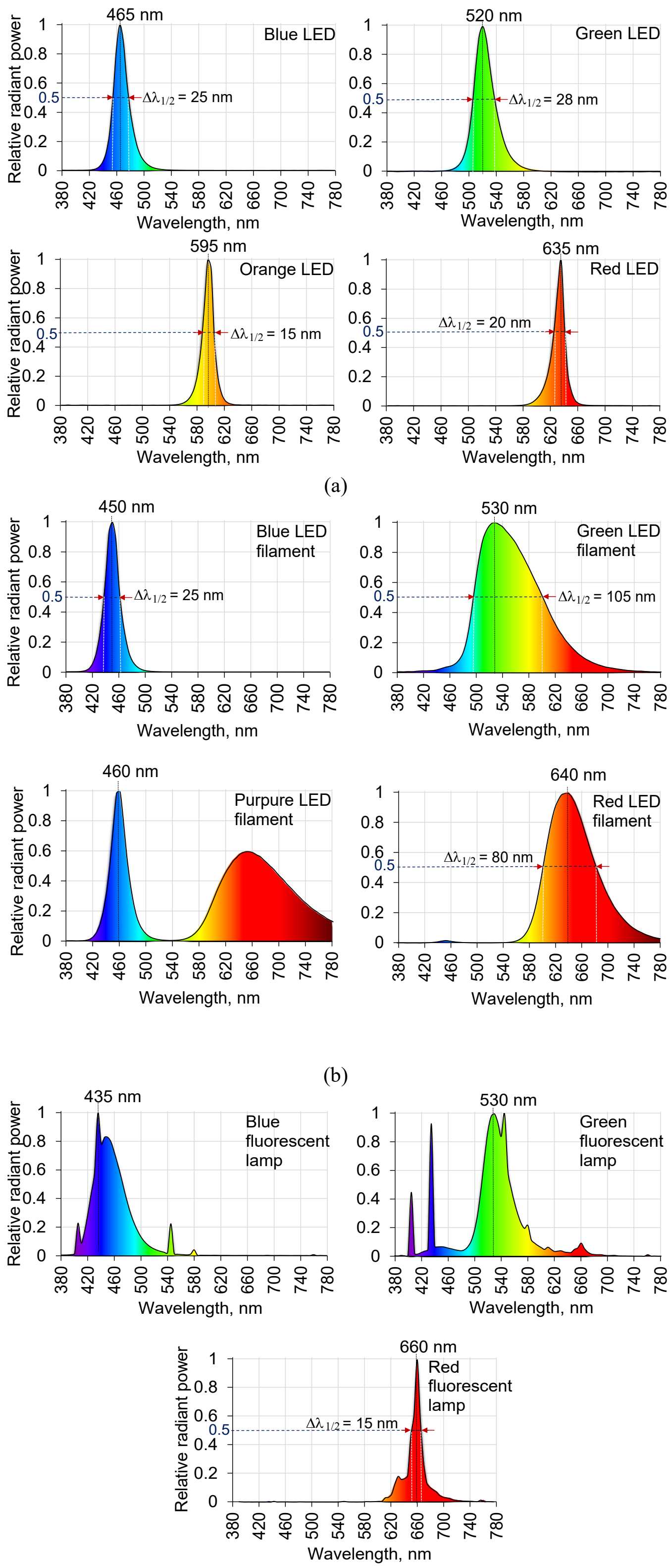


Fig. 3. Relative spectral characteristics of color light-emitting lamps: (a) SMD LED sources (b) LED filament (c) low-pressure fluorescent lamps

In the case of colored light sources, the color of the emitted light can be uniquely determined by providing a pair of numbers - coordinates x, y (in the case of the CIE 1931 system). The calculated chromatic coordinates for the 11 light sources based on their spectral characteristics (see Fig. 4) were plotted on the CIE chromaticity diagram (see Fig. 4). The CIE diagram represents how the human eye perceives the color of emitted light. The closer the chromaticity points are to the spectral locus, the more saturated the light color is perceived. This is the case for lamps with numbers 7, 9, 10, 11, as well as 1 and 2.

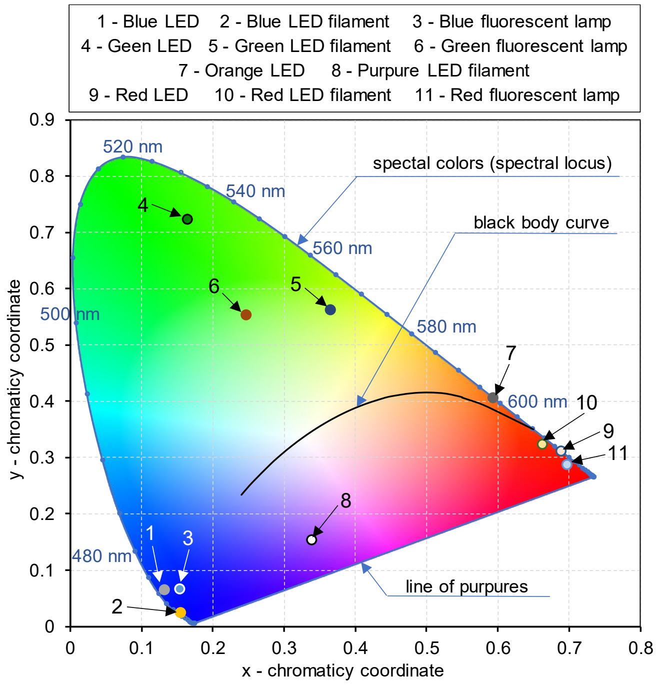


Fig. 4. Location of chromaticity points of 11 colored light sources on the CIE chromaticity diagram

C. *Description of the methodology for conducting the study*

Before conducting experimental measurements using colored light sources, the individual illuminance meters were calibrated at a characteristic point of 3 lx. In Poland, in photometric laboratories, illuminance meter calibration is performed using light standards. These are typically incandescent lamps with a color temperature of 2856 K [21]. The relative spectral distribution of such a lamp corresponds to Planck radiation (radiation from a perfect black body at a temperature of about 2856 K) [22]. It is worth noting that in the literature [23]–[25], the advantages of new reference LED sources are mentioned, however, these lamps are not yet widely used in laboratories.

The illuminance meters were calibrated at a station in a photometric darkroom. The main element of the station is a 6.5 m long photometric bench. It is equipped with components enabling precise determination of measurement geometry and a set of baffles to limit scattered light. At one end of the photometric bench, on a stationary cart, a light source is mounted. To limit scattered light (which affects measurement results, especially for low illuminance values), the light source is placed in a cage. The only opening through which light escapes is a circular aperture in the baffle. On the other side of the photometric bench, a illuminance meters photometric head is mounted on a movable cart. The movable cart runs on guides, allowing for changes in its position while maintaining linearity along the horizontal axis (the optical axis) of the photometric bench. The photometric bench also has a length scale, enabling the determination of the distance between the photometric head and the light source. During the calibration of the illuminance meters, an incandescent lamp with a color temperature of 2865 K was used, powered by a stabilized DC power supply. The calibration of each illuminance meter was performed 15 minutes after the incandescent lamp was turned on. The schematic of the measurement setup is shown in Figure 5.

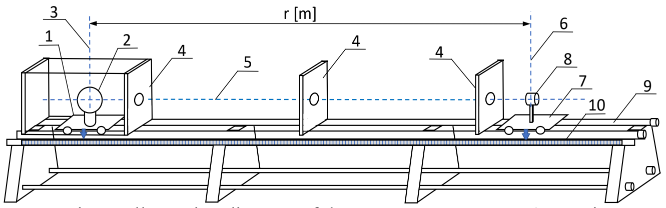


Fig. 5. Illustrative diagram of the measurement setup: 1 – stationary carriage, 2 – light source, 3 – vertical axis, 4 – aperture, 5 – horizontal axis (optical axis), 6 – vertical axis tangent to the active part of the photometric head, 7 – movable carriage, 8 – photometric head of illuminance meter, 9 – photometric bench, 10 – length gradation

In the further part of the study, the incandescent lamp was replaced with colored light sources. The light sources were powered by a voltage stabilizer, ensuring a constant effective voltage with an accuracy of 0.1%. Measurements were started 60 minutes after the colored light source was turned on. It was considered sufficient time for the light parameters of the lamps to stabilize [26]. The LMT 1-500 illuminance meter (Class L according to [27]) was used as a reference instrument. By adjusting the distance between the light source and the reference illuminance meter, the desired illuminance value (3 lx) was achieved.

IV. RESULTS

A. *Results of laboratory measurements - calibration*

In Figure 6, the relative error of illuminance measurement at the point of 3 lx is plotted for the 22 illuminance meter. The horizontal axis represents the illuminance meter numbers. The obtained results during calibration were used to calculate the relative error (represented by the vertical axis). Equation (1) was utilized for this purpose.

$$e_w = \frac{(E_w - E_x)}{E_w} \cdot 100\% \qquad (1)$$

where: E_w – reference value (3 lx), E_x – illuminance value indicated on the calibrated illuminance meter.

The relative uncertainty in determining the error does not exceed 2.5% with a coverage probability of approximately 95% and an expansion factor equal to 2.

Positive error values indicate that the reading of the tested photometer is lower. Negative values indicate that the readings of the tested illuminance meters are inflated. Analyzing the data shown in Figure 6, illuminance meters can be identified which, due to significant error values, are not predisposed for measuring low illuminance values.

The parameters describing the quality of illuminance meters are defined in the international standard ISO/CIE 19476:2014

[19]. This standard provides the limit values for errors. Table I includes only two parameters that are essential from the perspective of the issues addressed in the study. These are the spectral correction error f_1' and the total error. For low-quality photometers (Class C), the maximum allowable value for the total error should not exceed 20%. Analyzing the data presented in Figure 6, it can be observed that illuminance meters with numbers 9, 13, 18, and 19 do not meet this condition. However, it should be noted that Class C illuminance meters are more suitable for approximate measurements of illuminance. In the case of a complex measurement issue, such as recording low levels of illuminance produced by colored lamps, it seems reasonable to adopt the total error value at least for Class B.

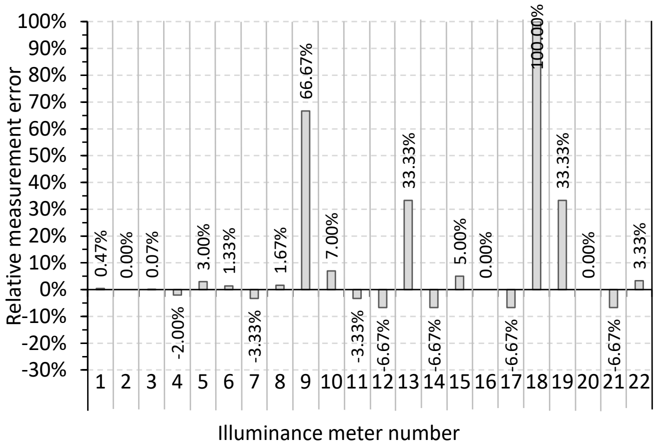


Fig. 6. Comparison of the calculated values of the relative error during the calibration of 22 different instances of illuminance meters (for 3 lx)

TABLE I
CLASSES OF ILLUMINANCE METERS AND THEIR CORRESPONDING VALUES

LIMIT VALUES OF SELECTED ERRORS

Parameter	Class L	Class A	Class B	Class C
Error f'_1	1.5%	3%	6%	9%
Total error	3%	5%	10%	20%

Since the legislator did not specify requirements for measuring instruments when defining the maximum illuminance value for colored light, it was decided to include all illuminance meters in further considerations.

B. *Results of laboratory measurements using colored light sources*

On Figure 7, the results of laboratory measurements for individual lamps emitting colored light are visualized. Due to the considerable number of measurements, the data were grouped based on the criterion of the color of light emitted by each lamp. The continuous black line indicates the value of 3 lx. Analyzing the data presented in Figure 7, it can be observed that despite the same lighting conditions, the readings of individual illuminance meters are divergent. The greatest discrepancies occur in the case of lamps emitting blue light, while the smallest discrepancies occur with green light. Due to the significant illuminance values recorded by some illuminance meters (Figure 7a), a portion of the vertical axis between 19 and 25 lx was removed. This adjustment helped reduce the size of the chart.

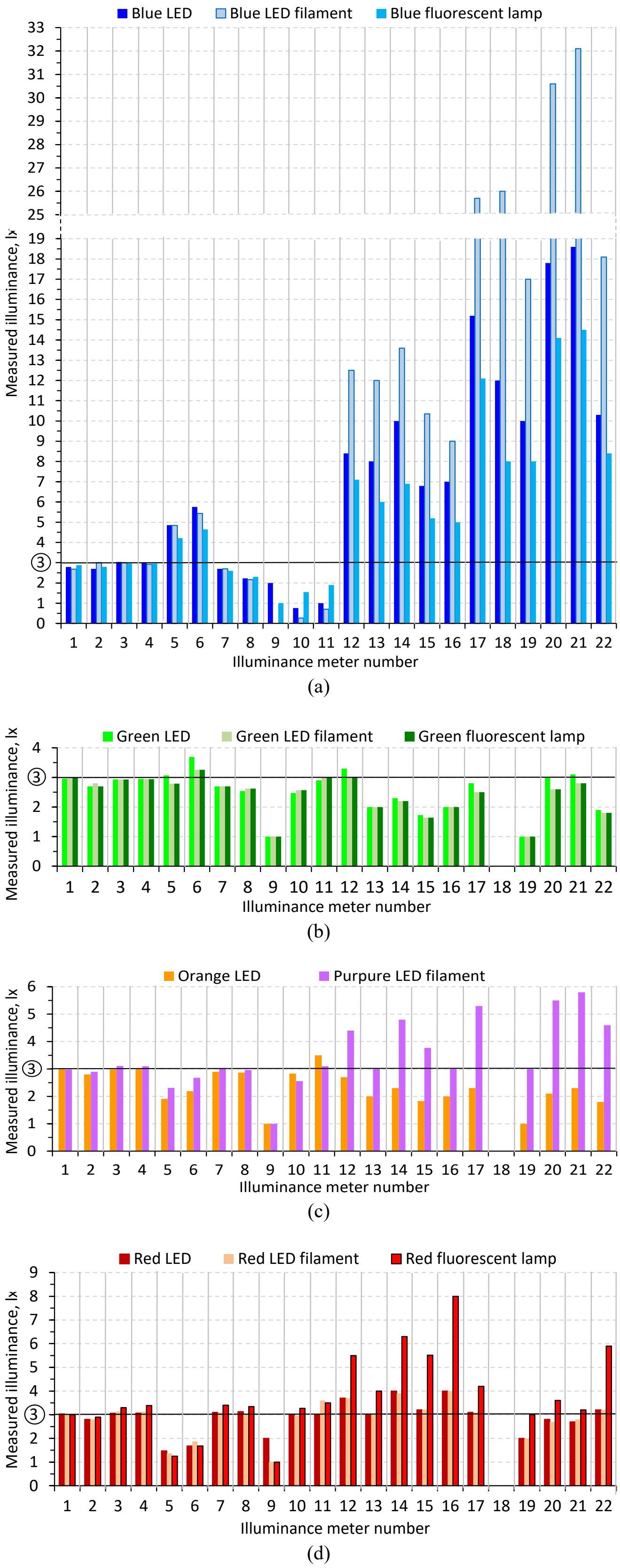


Fig. 7. Measured illuminance values with 22 illuminance meters for lamps emitting light of (a) blue, (b) green, (c) orange and purpure, (d) red colors

It's worth noting that among lamps emitting blue light, the least optimistic results were obtained for the LED filament source (lamp No. 2). This lamp, for which the peak radiation occurs at 450 nm, yielded the highest discrepancies in illuminance values recorded by some illuminance meters (illuminance meters No. 20 and 22) – over 10 times higher than the reference value of 3 lx. Smaller discrepancies were observed for the LED Blue lamp (lamp No. 1), where the peak radiation occurs at 465 nm. Meanwhile, the smallest discrepancies in measurement results were obtained for the blue fluorescent lamp, which emits light across a wider range of wavelengths.

Analyzing the data presented in Figure 7, it can be observed that one of the illuminance meters (illuminance meter No. 18) is capable of registering illuminance generated solely by lamps emitting blue light. The indicated values are several to several tens of times higher than the reference value of 3 lx. For other light sources, zero illuminance values are indicated.

C. Results of simulation calculations

If it is assumed that the spectral irradiance of the light source in the visible range is known, then using the spectral sensitivity of the human eye adapted for photopic vision (which is provided in tabular form [13]), illuminance can be calculated using equation 2.

$$E = K_m \int_{380}^{780} W(\lambda) \cdot V(\lambda)\, d\lambda \qquad (2)$$

where: $W(\lambda)$ – spectral irradiance of the light source ($Wm^{-2}mm^{-1}$), $V(\lambda)$ – relative spectral sensitivity of the eye adapted for photopic vision, K_m – photometric radiation equivalent, a constant whose value and dimension depend on the adopted photometric unit system (683 lm/W).

Usually, the spectral distribution of light source radiation is expressed in relative units (where the maximum radiation corresponds to a value of 1), while some spectrometers (calibrated in energy units) allow for registering the spectral distribution of a given light source in absolute units ($Wm^{-2}mm^{-1}$). In such a case, besides the spectral characteristic, the illuminance value is displayed, which has been determined based on Equation 2. If we assume that the value of illuminance determined in this way is 3 lx, then by replacing the expression V(λ) in Equation 2 with the spectral sensitivity curve of the actual photometric head of the illuminance meter S(λ), the obtained illuminance value will differ from 3 lx. In other words, the area under the curve resulting from the product of the quantities under the integral sign (Equation 2) is proportional to the illuminance. The larger the area, the greater the illuminance value.

Using Equation 2, simulations of illuminance were conducted for 22 illuminance meters, whose spectral sensitivity curves are shown in Figure 2. The calculations took into account 11 light sources, whose spectral characteristics are presented in Figure 3. These calculations are theoretical considerations as they only consider one aspect, which is the deviation of the spectral sensitivity curve of the photometric head from the reference curve V(λ). A graphical illustration of the calculation methodology is provided in Figure 8.

In the illustration of the calculation methodology, a blue LED source emitting light with a peak wavelength of 450 nm was used. Variant A represents the ideal (reference) case, where the spectral sensitivity curve of the illuminance meter corresponds to the reference curve V(λ). In such a scenario, the spectral mismatch error f_1' is equal to 0. In real-world conditions, perfect alignment of the spectral sensitivity curve of the photometric head with the curve V(λ) is not possible. Therefore, in Variant B, the curve V(λ) was replaced by the actual spectral sensitivity curve of the illuminance meter S(λ). To illustrate the significant differences in the obtained responses of the photometric heads between the ideal and real cases, the spectral sensitivity of illuminance meter labeled as 14 was selected (with an f_1' error of 51.17%). The photometric head of this illuminance meter exhibits significant sensitivity to blue light.

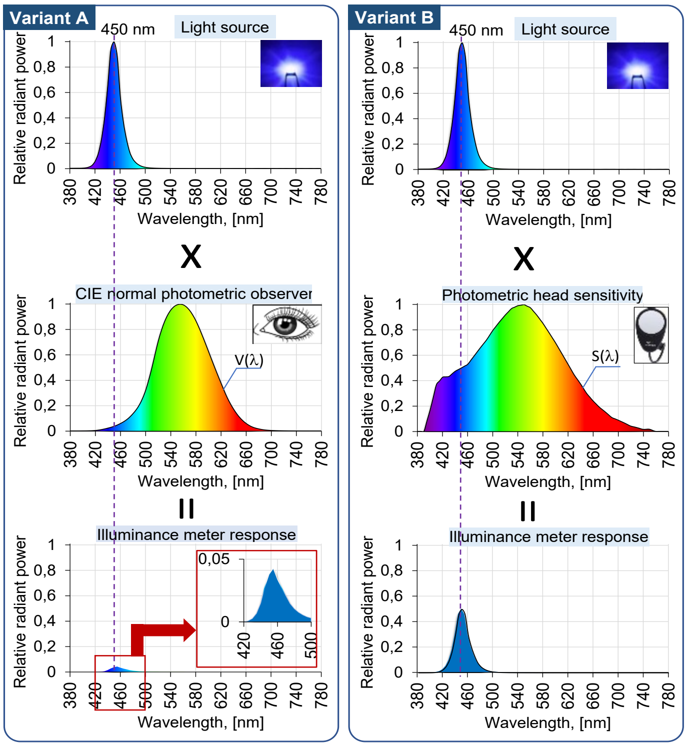


Fig. 8. Graphical illustration of the methodology of performing calculations to determine illuminance

Figure 9 visualizes the results of the simulation calculations. Similar to the measurements, the largest discrepancies in the calculated illuminance values were obtained for lamps emitting blue light, while the smallest discrepancies were observed for lamps emitting green light.

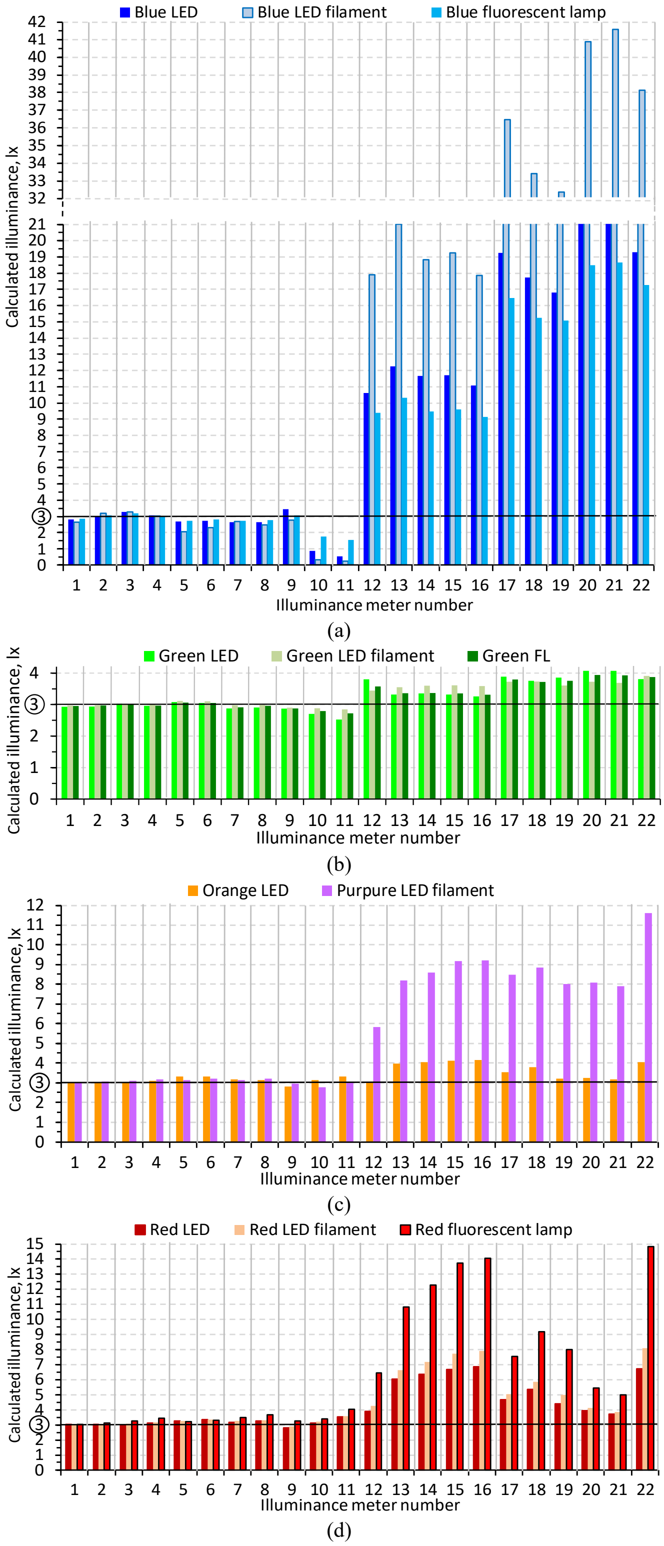


Fig. 9. Calculated illuminance values for 22 actual illuminance meter sensitivity curves and spectral characteristics of lamps emitting (a) blue, (b) green, (c) orange and purpure, (d) red light

D. *Comparison of results from measurements with simulation calculations*

Figure 10 presents the illuminance values resulting from laboratory measurements and simulation calculations. Due to the significant amount of data, only values for 4 photometers are provided. Two extreme cases were considered in the analysis, a photometer with the smallest and the largest f_1' error, as well as two selected (most popular) meters. Based on the number of photometers submitted to the Regional Office of Measures in Łódź (in the previous calendar year) for calibration services, photometers with numbers 4 and 9 were taken into account. The numerical values provided as percentages above the bars provide information about the difference between the measurement result and the calculation outcome.

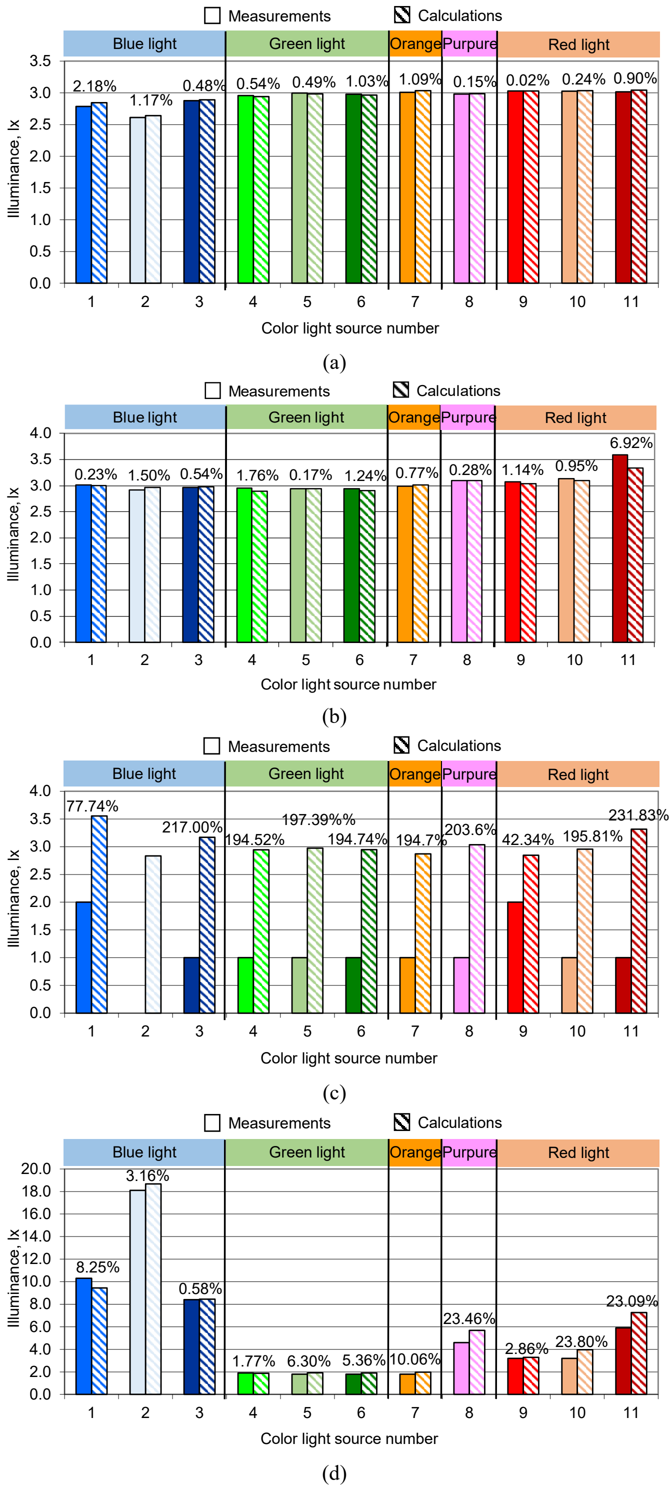


Fig. 10. Comparison of measured and calculated illuminance values for selected illuminance meters: (a) illuminance meter No. 1 (f_1'= 1.85%), (b) illuminance meter No. 4 (f_1'= 3.14%), (c) illuminance meter No. 9 (f_1'= 6.76%), (d) illuminance meter No. 22 (f_1'= 72.15%)

To determine the relationship between measured and calculated illuminance values, the Pearson linear correlation coefficient was calculated [28].

TABLE II
CALCULATED VALUES OF THE PEARSON'S LINEAR
CORELATION COEFFICIENT CORELATION COEFFICIENT

Illuminance meter	1	2	3	4	5	6
coefficient *r*	0.987	0.852	0.436	0.973	-0.867	-0.922
Illuminance meter	7	8	9	10	11	12
coefficient *r*	0.917	0.977	0.437	0.998	0.974	0.996
Illuminance meter	13	14	15	16	17	18
coefficient *r*	0.960	0.960	0.970	0.741	0.996	0.976
Illuminance meter	19	20	21	22		
coefficient *r*	0.994	0.998	0.998	0.993		

$$r = \frac{\mathrm{cov}(x,y)}{S_x S_y} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{n S_x S_y} \qquad (3)$$

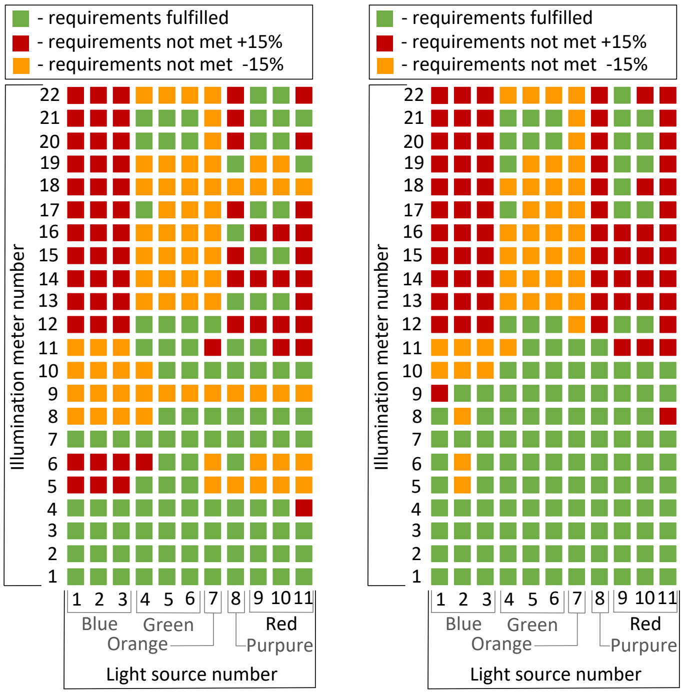
where: cov(x, y) – covariance is the arithmetic mean of the product of the deviations of the variable values x and y from their arithmetic means. $S_x S_y$ – is the product of the standard deviations of variable x and variable y, where variable x corresponds to the measured illuminance values, and variable y corresponds to the values resulting from calculations.

The coefficient r takes values from the range of -1 to 1. The closer the value of the coefficient is to 1, the stronger the correlation. The calculated coefficient values are presented in Table II.

Analyzing the data provided in Table II, it can be observed that for 15 photometers, the r coefficient is greater than 0.9, indicating a very strong linear correlation between the results of laboratory measurements and the calculated results. This means that for these photometers, the spectral sensitivity of the photometric head is a significant factor influencing the measurement results. For the remaining photometers, this correlation is smaller or does not exist at all, indicating that other factors significantly affect the measurement results.

In Figure 11, the assessment of individual photometers regarding the obtained illuminance values at the characteristic point of 3 lx is visualized.

Because measurements of colored light at low illuminance levels are a challenging metrological issue (due to numerous sources of error), it seems necessary to adopt a tolerance between the assumed value and the measured and/or calculated one. The authors propose adopting a tolerance of ±15%. This means that the determined illuminance value should fall within the range of 2.55-3.45 lx. Readings of photometers for which the obtained values fall within the specified range are marked with a square filled with green color (Figure 11). Values exceeding 3.45 lx are marked with a square filled with red color,



(a) (b)

Fig. 11. Graphic illustration of the evaluation of photometers in terms of illuminance values resulting from (a) laboratory measurements, (b) calculations

while values below 2.55 lx are marked with orange color. Adopting such reasoning allows us to identify which photometers tend to overestimate or underestimate the illuminance values for individual light sources. The idea behind this approach is to indicate which photometers may be potentially predisposed to measuring illuminance concerning light pollution assessment. Analyzing the data presented in Figure 12, four photometers stand out for which the evaluation results for all lamps are positive, both in terms of illuminance determined based on laboratory measurements and based on calculations performed. These are photometers with numbers 1, 2, 3, and 7.

DISCUSSION

Measurements of low illuminance levels (3 lx) are associated with a high risk of obtaining results that do not reflect the actual lighting situation. Most calibration laboratories do not determine measurement errors for such low values during calibration. Therefore, users are unaware of the metrological characteristics of their instruments in this range.

In Poland, the price is often a significant criterion when choosing a illuminance meter. Unfortunately, there is a high demand for inexpensive illuminance meters, which usually have low quality. It is worth noting that illuminance metres are currently not subject to legal metrological control, which would allow only those photometers that meet the requirements set out in the regulations to be used. Calibration laboratories do not have the competence to indicate to users of meters the limitations on the use of photometers. In other words, there is a lack of tools to control the quality of illuminance metres used for field measurements.

One solution is to calibrate the device with an assessment for compliance with requirements [29]. However, the user must specify these requirements and the decision-making process for the assessment, allowing for flexibility in approach. Furthermore, the assessment for compliance with requirements is not mandatory.

When assessing intrusive light based on measurements taken by two different illuminance meters, there is a real risk of obtaining conflicting opinions. This poses interpretational challenges, especially in contentious situations when residents complain about bright illuminated advertisements, illuminating the interiors of their bedrooms.

One could argue that for measurements of colored light, illuminance meters with an f_1' error not exceeding 3% are acceptable. However, it is worth noting that this parameter applies to the entire visible range. Therefore, it may happen that as the f_1' error value increases, the obtained measurement results may not necessarily be less optimistic. Such a situation occurs in the case of number 7.

Not all illuminance meter manufacturers provide the f_1' error value in their technical specifications. This situation occurs with cheaper illuminance meters. Instead of the f_1' value, you may encounter a very general indication of the spectral correction applied to the photometric head to match the V(λ) curve. Choosing such a illuminance meter for measurements aimed at assessing intrusive light, such as light from colorful advertisements, is very risky. Measurement errors can be significant, which may result in issuing incorrect opinions.

Due to the aging of illuminance meter components, it is recommended to periodically recalibrate them at low light intensity values (as is the case with illuminance meters used to assess the parameters of emergency lighting).

The measurement results presented in the paper were obtained under laboratory conditions at a temperature of (25 ± 1)°C. This is the standard ambient temperature adopted in the norm [30] concerning photometric measurements. Conditions during field measurements differ from those in the laboratory. The temperature after sunset is usually lower, which will affect the measurement results. With the decrease in ambient temperature, one must consider changes in the sensitivity of the illuminance meters photometric head, as well as changes in the luminous flux and spectral characteristics of the light sources installed in the illuminated signs. Regulation [9] does not define the conditions under which measurements should be conducted. There is also no mention of the need to consider other potential light sources (such as vehicle lights, moonlight), which may affect the increase in lighting levels.

Conclusion

The conducted research allows us to conclude that controlling light pollution from colored illuminated advertisements is a challenging measurement issue. It can be argued that the requirement outlined in Regulation [9] is more stringent than the guidelines for evacuation lighting. The fundamental problem to be noted in connection with measuring illuminance is the issue of selecting the appropriate meter.

The responsibility for conducting measurements and issuing opinions based on them lies with the meter user, so the choice of a photometer is crucial.

The biggest issue with assessing intrusive light was observed in the case of lamps emitting blue light. The reason for this is that the greatest deviations of the sensitivity curve of photometric sensors from the reference curve V(λ) usually occur in the range of shorter wavelengths.

Upon analyzing the obtained results from measurements and calculations, it can be concluded that an increase in discrepancies in measurement results can be expected in the case of light sources whose peak radiation falls at the edges of the visible spectrum. The width of the spectral distribution is also significant. The narrower it is, the greater the measurement error should be anticipated.

In the conditions encountered during field measurements, additional factors will influence the measurement result, such as ambient temperature, the presence of other light sources, and spatial correction. Therefore, it seems justified to adopt an appropriate tolerance when assessing compliance with requirements. In the regulation, tolerance regarding illuminance values was not specified. This means that any value exceeding 3 lx will be equivalent to issuing a negative opinion regarding compliance with the requirements for limiting intrusive light. According to the authors, the statement "cannot exceed 3 lx" should be interpreted with a tolerance of, for example, +15%.

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