Dariusz SAWICKI[1], Agnieszka WOLSKA[2], Tobias PORSCH[3]

Warsaw University of Technology, Institute of Theory of Electrical Engineering, Measurement and Information Systems, Warsaw, Poland (1), Central Institute for Labour Protection - National Research Institute (CIOP-PIB), Warsaw, Poland (2), TechnoTeam Bildverarbeitung GmbH, 98693 Ilmenau, Germany (3)

doi:10.15199/48.2019.01.43

Glare assessment for research and development of measurement methods

Abstract. *Glare is one of the most important parameter of lighting quality. Despite the passage of time from the beginning of glare research, no standard of conducting laboratory experiments was proposed. In the article the review of solutions related to glare assessment is presented. The method of conducting research on glare is also described. The authors pay attention to the most important aspects in the methodology of glare assessment for the experimental research on glare and glare assessment based on UGR measurements. The tests of the new algorithm for UGR calculation is presented — algorithm for precise identification and extraction of glare source area from HDR image.*

Streszczenie*. Olśnienie jest jednym z najważniejszych parametrów jakości oświetlenia. Pomimo upływu czasu od rozpoczęcia badań nad olśnieniem, nie zaproponowano żadnego standardu prowadzenia eksperymentów laboratoryjnych. W artykule przedstawiono przegląd rozwiązań związanych z oceną olśnienia. Została także opisana metoda prowadzenia badań nad olśnieniem. Autorzy zwracają uwagę na najważniejsze aspekty metodyki oceny olśnienia w badaniach eksperymentalnych nad olśnieniem oraz metodyki oceny olśnienia w oparciu o pomiar UGR. Przedstawiono testy nowego algorytmu wyznaczania wskaźnika UGR; algorytmu precyzyjnego wyodrębniania obszaru źródła olśnienia na obrazie HDR. (****Ocena olśnienia dla badań i rozwoju metod pomiarowych)****.*

Keywords: discomfort glare assessment, experimental research on glare, UGR measurements, algorithm for precise identification and extraction of glare source area
Słowa kluczowe: ocena olśnienia przykrego, eksperymentalne badania nad olśnieniem, pomiary UGR, algorytm precyzyjnego wyodrębniania obszaru źródła olśnienia

Introduction

Light plays a very important role in a human life, especially artificial light allowing work and perform any activities after dark. Glare is one of the most important lighting quality parameter. It is accompanying the process of vision that affect human visual comfort, wellbeing and performance. It could be also the indirect reason of accidents at workplaces and other illuminated public and private areas. Depending on the type of glare (discomfort, disability, blinding) the accompanying risk is of different level [1]. International standards and CIE documents define rules for discomfort glare assessment and application of relevant index: Unified Glare Rating (UGR) for indoor workplaces [2, 3, 4]. Additionally the development of application of imaging luminance measuring device (ILMD) allows for practical measurement of UGR.

The formula for UGR determination and related requirements for maximum limit values of UGR are known for many years. However the studies concern glare assessment are still being carried out. They concern both exploration for a new glare metrics and development of new measurement methods for objective glare assessment.

It is worth noting at this point that the measurement of glare refers to two independent issues:

- measurement under real conditions in order to assess the glare, based on UGR determination,
- measurement for testing glare perception under different glaring conditions and for the development of measurement methods.

Conditions and rules of both issues of glare measurements are different.

Despite the passage of many years from the beginning of glare research, no standard of conducting laboratory experiments was proposed. Each researcher conducts study according to his own original method and his own procedures, using equipment available in his own laboratory. This is due to the variety of factors affecting glare and the complexity of the research process. It is also difficult to find a review article concerning measurement methods used in experimental research on glare. The aim of this article is to present methods of assessment, measurement and evoking the glare for research and development of measurement methods.

Glare — a hundred-year old history of research

The studies on glare arising from artificial light sources have been carrying out for more than 100 years. The first document concerning glare was written in London in 1910 [5]. Sir John Parsons has analyzed in it many examples of situations in which people experience glare. In 1926 Holladay [6] described how glare affects visibility taking into account different kind of glare including blinding glare. But the publications related to discomfort glare appeared in the 40s of the twentieth century. One of the main precursors of research focused on discomfort glare assessment was Ralph Galbraith Hopkinson. He introduced multiple-criterion scale for discomfort glare assessment, which is often used in glare studies until today. Hopkinson's multiple-criterion technique [7, 8], was the basis of the UGR — the current method of discomfort glare assessment in indoors, which has been introduced in 2002 to requirements of European standard EN 12464-1 [2]. Semantic scales of glare used nowadays are based on the works of Hopkinson [9, 10, 11] and de Boer [12, 13] from the 60s and 70s of the twentieth century. Despite the passage of time, these scales allow evaluating sensation of glare under different conditions in contemporary applications. On the other hand, the studies on unification or extension of the semantic scales of glare are still carried out [14, 15].

The experimental research on discomfort glare

For many years the studies have been dedicated both the measurement aspects and perceptual aspects of discomfort glare arising from artificial glare sources at indoor workplaces. Some review articles concerning discomfort glare are known, like consideration of lighting parameters (glare as well) on well-being in office environment [16] or the state of the art of discomfort glare [17]. The review of factors influencing discomfort glare from daylight [18], but in case of glare from artificial lights many factors and properties are very similar. Particular studies about glare are dedicated to single (isolated, if possible) factor affecting the glare sensation.

Since the UGR formula has limitation concerning the source solid angle (not valid for sources of projected area smaller than 0.005 m^2 or larger than 1.5 m^2) many studies were dedicated to develop extension of the UGR formula for small sources [19, 20] or large sources [21, 22]. The glare sensation depends also on: glare source spectral distribution [23, 24], the intermittent or constant duration of exposure to glare [25] and the range of luminance of glare presented during the experiment [26]. The different location of the glare source relative to the observation line (central or peripheral glare) also influence the glare perception [27 – 30]. Difficulty of task has been shown to have influence on glare assessment [31, 32]. The luminance uniformity or non-uniformity of glare source became as an often studied factor influencing glare, especially for LED sources [33 – 44].

The studies on perception of discomfort glare showed a large variance in participant response, and some showed low correlation between predicted values and participant response [45 – 47], but the other studies showed high correlation [48 – 50], what suggested that UGR is the best predictor of discomfort glare at indoors [42]. But this conclusion do not concern LEDs sources because all current glare metrics are inadequate to evaluate glare from LEDs [33, 35 – 41, 44, 51 – 55].

It is worth to mention that psychological factors and demographic variables of subjects play important role [31, 32, 56, 57].

It could be seemed that almost all possible factors influencing discomfort glare were already taken into account and everything is well known about glare phenomena. But it is not the true. The basic mechanisms that lead to discomfort glare perception are still a little known [42], especially for new generation light sources — LEDs. The question about the additivity of sources in glare analysis also returns [17, 58]. The importance of glare assessment is underlined by International Commission on Illumination (CIE) in the document entitled "*Research Roadmap for Healthful Interior Lighting*" [59], which was published in 2016. One of the main problem that has been raised by CIE as a research challenges concerns the evaluation of the degree of glare caused by LED, which became widely used for illumination of indoor and outdoor areas.

Methods and equipment used in research on glare

The experimental studies on discomfort glare assessment are conducted on the individually designed experimental stands under controlled lighting environment, what gives a huge range of glare simulation methods. There is a large diversity between experimental procedures and glare conditions used in laboratory studies. The most important differences are related to glare source features and its presentation in the visual field during the experiment.

Laboratory environments for glare studies can be divided into two groups. The first, where the tests are carried out simply in a typical laboratory room. In this solution, attention is focused primarily on the appropriate arrangement of sources of glare and controlling its level. The second, where special apparatus or lighting chamber have been built to conduct specific and specialized research.

In the first group, the simplest solution is to put all elements (optical equipment, glare sources) on the table in controlled distances [23, 60].

The windowless room with a typical classroom furniture and a set of different light sources mounted on ceiling was used in the study described in [61]. In such a rooms special constructions can be also used to obtain a large size of light source, but with the possibility of dividing into smaller fragments: 40 fluorescent tubes behind opal acrylic plate [62], 16 fluorescent tubes behind opal plexiglas with additional set of cool-white lamps and sylvanian phosphor lamp [63], 16 incandescent light bulbs (independently controlled) diffused by opal plastic screen [21]. There is also known special adjustable-size apparatus that allows obtaining diamond shape glare source with variable, controlled sizes [64]. Nowadays arrays of LEDs are often used: as a sources mounted on ceiling [38], or on the wall [35, 44]. LEDs enable the easy change of color temperature [65] and simulation of uniform or non-uniform luminance of glare sources. [35]. In all such cases independently controlled lamps (or parts of large sources) and array of LEDs allows simulating several different sizes and positions of glare source.

The most advanced form of using the laboratory for glare research is to build a special room (equipped, furnished and decorated) reflecting the character of the workplace (or other activity). In this case, the tests are carried out in the conditions closest to the real ones. Office rooms [35, 66, 67] or living room [66] are usually built. The Authors of [68] used model of room in scale 1:12, equipped by dolls furniture. Special (dedicated) rooms are also built in order to equip them with appropriate large sets of cameras or other sensors [69, 70].

In the second group, special large apparatus are used in laboratory for glare testing. Researchers have built large semi-spherical screen in size: radius of 0.33m [71], or 1m [72 – 74]. The apparatus was equipped in light sources for simulating glare sources and obtaining proper level of background luminance. The authors used halogens lamp box [71] or arrays of 3136 LEDs [72, 73]. Similar idea but different shape of apparatus is described in papers [75 – 77]. Experimental lighting chamber in semi-hexagonal plan has been built [75, 76]. The chamber consists of 3 walls (0.7m x 2.7m) with independent two kind light sources: LEDs for creating background, and projector controlled by computer as a glare source. Four walls hexagonal chamber is described in [77]. Authors used two projectors behind diffusing screens (back-projection) and one opal incandescent lamp (as the reference source) for glare simulation.

Different methods of performing the experiments and different glare source simulation do not allow deriving clear conclusions which arrangement of experiment could be better. The construction of a special environment (semispherical or hexagonal chamber) facilitates control of parameter significantly. However, such environment significantly differs from real conditions. It seems that the use of a natural environment (e.g. an office room) gives better comparative conditions for glare assessment. Although it requires more effort in selecting, changing and measuring of parameters. However, in such a situation, the laboratory measurements are carried out in conditions most similar to the real measurement conditions.

The crucial rules for experiments with glare

The aim of making measurements related to glare under the real workplace conditions is to determine the index value (UGR) in a specific place to assess existing level of discomfort glare. It is expected that the assessment is reliable (properly made) and the measurement procedure is as simple and quick as possible and obtained results burdened with possibly the slightest error. Such a measurement must be done correctly for the first time, because in practice there is no time or possibility to repeat the measurement.

The purpose of tests in laboratory conditions is slightly different and is correlated to the particular aim of the research. Hence, we expect the following conditions to be met:

- Repeatability of experiment conditions. Stability is not only important during the particular experiment — experiment is sometimes repeated deliberately for similar settings to validate certain hypothesis. In the case of lighting testing, this means, among other things, the stability over the time of: the glare sources and background luminance, invariable position of observer and all relevant measurement instruments. Documentation of the experiment should give the possibility to conduct a similar test in another laboratory.
- Compliance with real conditions. We expect that laboratory conditions reflect the real conditions well. The goals of research are almost always associated with certain applications or with development (of methods or equipment) for practical purposes. Dedicated rooms (in natural or reduced sizes) are great options. On the other hand, it is difficult to fulfill this condition in the case of chamber of hexagonal or semi-spherical shape.
- A wide range of applicability and scalability of the problem. The results of the experiment should give the opportunity to refer to real conditions to the possible widest extent.
- The ability to control independently relevant parameters. The glare measurement is a very complex task — the transposition of the real conditions into experimental conditions is related to the control of the following parameters: luminance of the background, luminance of sources of glare, position of glare sources, size (viewing angle) of glare sources.
- It is important to ensure a fixed and stable position of the observation / measurement point. The most commonly used is chin-rest for the position of participant's eyes and tripod with proper head for positioning of camera.

Technical aspects of glare assessment based on UGR measurements

Standard [2] and CIE documents [3, 4] define parameters and rules how UGR should be determined. Nowadays measurement of glare at indoor workplaces is performed using of imaging luminance measuring device (ILMD). ILMD allows obtaining luminance map from proper point of view and based on it UGR is calculated. Practically, as ILMD, proper calibrated camera is used. Standard [2] does not specify the size of angle which should be analyzed in UGR calculation. It means that it is not precisely defined viewing angle of camera (ILMD) for determining the luminance map. It is therefore assumed that it should cover the human field of view. In this way the combination of sensor array of camera and focal length of the used lens determine the view angle of ILMD. In most cases the fish eye lens is used. In this way in measurement under real conditions, to determine the UGR, the following set of instruments is enough: ILMD (camera) with a fish eye lens, a stable tripod and a spirit level to verify the ILMD position.

In the case of experiments and research we are interested also in more flexible setting of parameters. The possibility of changing the direction and viewing angle in a convenient way is expected. A second lens with a smaller (than fish eye) angle of view turns out to be very useful because it allows taking images with better angular resolution than fish eye lens.

Additionally, assuming the fixed point of camera position, professional photographic head allows rotating around any axis, and this way selecting right direction of measurement. It is worth paying attention to parallax error which can arise. This error can influence the creation of luminance map and therefore change the value of UGR calculation. In laboratory conditions, we can control the position of each element (each light source), but rotation of the ILMD may cause, for example, obscuring the source by other objects as an affect of parallax error. This is due to the fact that the rotation can be related to the change (shift) of point of view, associated with the lens — and optical parameters ceases to be fixed. The use of professional panoramic head allows eliminating the problem of parallax error. With such a head ILMD is rotated around No Parallax Point (NPP) [78]. Commonly, although incorrectly, this point is called Nodal Point. Calibration of the head should be done in the laboratory individually for each camera - lens combinations. In calibration entrance pupil database [79] can be used, or proper algorithm [80].

The last very important technical problem concerns the range of luminance which have to be covered by luminance map for UGR calculation, and which often significantly exceeds the abilities of an ILMD's sensor. This problem is solved by using high dynamic range (HDR) method [81]. In measurement under real conditions, one proper exposed HDR image is enough to calculate UGR. In the case of experiments and research it is often worth taking many images in different exposure conditions. This allows assessing the impact of changes independently for various parameters, however the changes of exposure parameters should be made very carefully and analyzed in relation to the proper luminance map.

In our experiments we used LMK Mobile and Advance device from Techno Team [82] in our research. This ILMD is based on a Canon digital camera (model EOS 550D with APS-C CMOS sensor, 5184 × 3456 pixels). The set from Techno Team includes also two calibrated lenses — Sigma's 4.5 mm F2.8 EX DC HSM Circular Fisheye and Sigma's 17-50mm F2.8 EX DC OS HSM.

Fig. 1. View of the ILMD mounted on the panoramic head: 1 — rotator for rotation in the vertical axis; 2 — rotator for rotation in the horizontal axis; 3 — leveler allowing for the level setting by three independent screws.

For the purpose of our experiments we have built panoramic head on the base of Arca-Swiss system. Additionally two rotators are mounted to panoramic head on the tripod (Fig. 1.). Such combinations of instruments allows rotating the ILMD device independently in the horizontal and vertical plane without changing the position of the center of rotation (around the NPP point). The use of two rotators, as shown in Figure 1, allows obtaining (in two rotational axes) fixed, preset, and repeatable angles of rotation (e.g., every 10°, 20°, or 45°). It is very useful in laboratory experiments — it facilitate the correct setting of the ILMD during laboratory measurements and additionally allows minimizing geometrical errors.

The dynamic range of the sensor of Canon 550D covers approximately 7 EV–8 EV [83]. The HDR method allows increasing the range by 4 EV. In this case 3 pictures are taken in Auto Exposure Bracketing mode (AEB mode) [84], and known algorithm [85] allows setting proper exposure conditions.

Experimental environment in CIOP-PIB

Study concerning glare have been conducted in Central Institute for Labour Protection – National Research Institute (CIOP-PIB) for many years. Three independent laboratory rooms have been used.

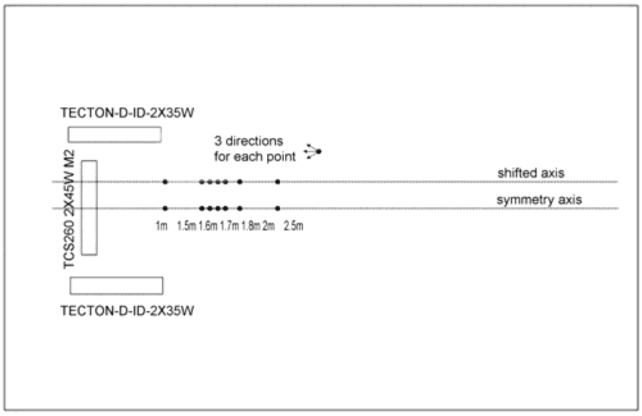

Fig. 2. Arrangement of glare sources and set of observer's locations in room A. Locations of the measuring points were described by distance from the central luminaire, respectively: 1 m, 1.5 m, 1.6 m, 1.7 m, 1.8 m, 2 m and 2.5 m.

- **Room A**. Typical office room with desk, computer and other furniture measuring 7 m x 4,5 m x 2.9 m. Wall and ceiling reflectance: 0.7, floor reflectance - 0,3. Three luminaires on the ceiling and set of 14 points (marked on the floor) to carry out measurements in a fixed, controlled and repeatable manner. 7 points are located on the symmetry axis of the luminaires set and 7 on the parallel line to this axis but shifted of 0.45 m – Figure 2. For each of the points we used to assess glare for three direction of observation: straight ahead (to the glare sources) and for direction rotated by 30° from the axis (left and right). Each light source can be used independently, and additionally we can use portable small sources to change lighting conditions. In order to control exposure conditions we use also gray cards Figure 3. For experiments with people we use chin-rest to fix participants eye position.
Wide set of combination of lights, observer's location and direction of observation, allow selecting all parameters influencing glare: luminance level and luminance distribution in the visual field, different positions of glare source and different solid angle of glare source.
- **Room B.** A laboratory room with white walls, a gray ceiling, and a gray floor measuring 8.6 m × 4.3 m × 3.5 m. The walls and ceiling reflected light in a diffused way in this room (reflectance 0,9), floor reflectance 0.3. .
- **Room C.** A laboratory room with black walls, ceiling, and floor measuring 10 m × 4.5 m × 4.5 m. The floor and the wall in front of the observer (the background of the source) reflected the light in a directional diffuse way; reflectance 0.15.

Two laboratories (B and C) allows conducting experiments in extremely different lighting conditions. In addition, to a certain extent, they allow for free arrangement of space. The reflectance coefficients of individual planes (walls, floors and ceilings) in all rooms have been measured so that we could apply them in the simulation calculations in the DIALux software.

We use different light sources in our experiments. Fixed sources (Figs. 2 and 3):
- S1 central luminaire in Room A: TCS 260 2x54W M2 (Philips Lighting). The maximum luminance 46700 cd/m².
- S2 and S3 sides luminaires in Room A: TECTON-D-ID 2x35W (Zumtobel). Possibility of luminance change in the range of 300 cd/m²–20200 cd/m².

Portable sources:
- S4 (Fig. 3) Waldman luminaire with circular fluorescent lamp and incandescent tungsten lamp (40W); the maximum luminance of 72 000 cd/m².
- S5 (Fig. 4) MASTER LED bulb MV 12W (2700K); maximum luminance of 57 500 cd/m².
- S6 Ledvance Floodlight LED luminaire 20W / 3000K with maximum luminance of 440 000 cd/m². It is a luminaire with a luminous intensity distribution close to diffused.
- S7 Ledvance Spot LED 6.5W / 3000K with maximum luminance of 2 200 000 cd/m². It is a luminaire for spot-lighting with a directional light distribution emitting a luminous flux in an angle of about 36°.
- S8 Fluorescent luminaire with frosted and textured glass diffuser Maxi 1 × 36 W (RZB Rudolf Zimmermann) with maximum luminance of 26 000 cd/m². It is a luminaire with a diffused luminous intensity distribution.

S6 – S8 are used only in Room B and Room C. All portable luminaires (glare sources) can be installed on photo tripods or stands, so that they could be placed in any places of the room and emit light in any chosen direction.

Fig. 3. The observer's field of view in the laboratory (room A)—three fixed luminaires (S1,S2,S3), two portable sources (S4,S5), and two different gray cards (G1,G2) for exposure calibration.

Laboratories with different, but controlled lighting conditions, and a wide range of applied glare sources allow to conduct glare tests assuming any lighting conditions and values of UGR parameters. In practice, for all established measuring points in Room A, simulations have been made in DIALux software. At the same time, different levels of luminance for fixed luminaires (glare sources) were assumed. In addition, studies with people were carried out many times in this laboratory [57]. Subjective assessment of glare sensation confirmed the correctness of UGR measurements. On the other hand, the conditions in Room A correspond exactly to the office conditions, nothing has to be simulated or pretended. This gives the opportunity to conduct trustworthy and reliable research corresponding to real conditions.

Experimental testing of the new algorithm developed by TechnoTeam

In 2015 and 2016 in the laboratories of CIOP-PIB we conducted a series of experiments, which concerned the testing of a new algorithm for calculating UGR. The new algorithm was developed by TechnoTeam Company.

One of the difficulties in the evaluation of discomfort glare using ILMD is the correct identification of the glare source. In practice, the simple threshold method has been used for many years. It allows, based on the histogram analysis, to select the areas of the source of glare on the luminance map. However, the typical HDR image and non-uniformity of the light sources make these issues a lot more complicated. Therefore the new algorithm has been introduced by TechnoTeam in order to simplify identification and extraction of glare sources, especially of non-uniform luminance distribution.

The proposed method for an automated filtering of the glare sources in the luminance map uses a local contrast threshold. The local contrast can be calculated using formula (1).

(1) $$C_{loc(\vartheta_i,\varphi_j)} = \sqrt{\left(\frac{\partial L}{\partial \vartheta}\right)^2 + \left(\frac{\partial L}{\partial \varphi}\right)^2}$$

And on the luminance map derivatives can be calculated using equations (2) (3).

(2) $$\left(\frac{\partial L}{\partial \vartheta}\right) = \frac{L(\vartheta_{i+1},\varphi_j) - L(\vartheta_{i-1},\varphi_j)}{L(\vartheta_i,\varphi_j)}$$

(3) $$\left(\frac{\partial L}{\partial \varphi}\right) = \frac{L(\vartheta_i,\varphi_{j-1}) - L(\vartheta_i,\varphi_{j+1})}{L(\vartheta_i,\varphi_j)}$$

Where $L(\vartheta_i, \varphi_j)$ is the local value on the luminance map and ϑ_i, φ_j described position in luminance map using vertical and horizontal angles.

The proper threshold C_{loc} was determined experimentally. The C_{loc} = 0.25 allows recognise glare sources effectively [86]. A typical effect of the new algorithm — automatic extraction of the source of glare is shown in Figure 4. Automatic detection greatly simplifies image processing during UGR calculation. It gives the possibility of a comfortable and quick assessment of the glare. Details of the new algorithm and software applications can be found in [87].

The experiments were carried out in Room A. Various ILMD settings were taken into account: changes in the horizontal plane (device's rotation) and changes in the distance from the sources of glare — in the full range of settings provided in the laboratory (1m - 2.5m). This allowed obtaining various positions of glare sources in the field of view, and different solid angles in which glare sources were visible. In comparisons, the methods of glare determination were considered:

- UGR determined by the new algorithm (with local contrast threshold).
- UGR determined using the old algorithm (manual or automatic threshold — without local contrast threshold).
- UGR determined in the DIALux simulation.
- subjective glare evaluation on a large group of people (previous studies under the same conditions [57]).

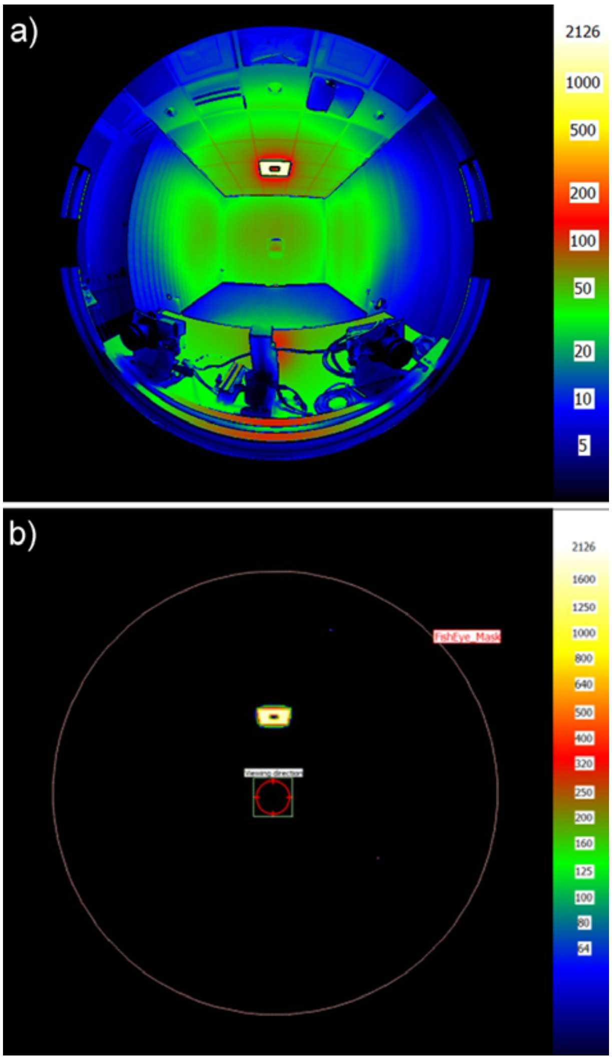

Fig. 4. a) Map of luminance analyzed by the new algorithm. b) detected source of glare as an extracted region of luminance map.

Analysis of the first results gave quite surprising results. In almost all cases, for different positions, there was a specific tendency:

- UGR calculated in the old algorithm was higher than UGR from DIALux simulation,
- UGR calculated by the new algorithm was lower than UGR from DIALux simulation.

But deeper analysis of both algorithms and results allowed determining the reason of such tendencies. We stated that different approximation of the solid angle for the viewing field of light sources used in both algorithms, was the main reason. This approximation is dependent on the luminance threshold level, which was different in both algorithms. The changing of the algorithm and setting of proper identical thresholds allowed to obtain the expected very similar results of UGR. The selection of the threshold value takes place automatically in the new algorithm — which is its unquestionable advantage.

The experiments in our laboratory allowed in simple way preparing and determining geometric parameters for the tests of specific properties of the algorithm. And most importantly, everything took place in real office conditions, giving the opportunity to obtain trustworthy and reliable results of analysis.

Summary

Research on glare are complicated, require not only a set of appropriate instruments, but also a large, very well arranged space. The aim of the paper was to present methods of glare assessment for research and development. We have made an attempt to review solutions related to glare assessment. However, not in terms of methods and practical applications, but in terms of how to conduct research on glare. Many different approaches are used — knowledge about them can be useful in further research.

As an example, we showed testing of a new algorithm for determining UGR. Testing in simple, specific but controlled conditions allowed checking the properties of the new solution. In addition, the real conditions in which this took place, increased the usability of the conducted research. The new algorithm has been verified — the tests confirmed its correctness.

Practical assessment of the glare, for example to check whether certain standards are met at the workplace, is one important issue, and assessment for research purposes is another. We tried to pay attention to the most important differences, as well as to show what is important in the applications for the research. Investigations concerning glare are still continued. The development of new light sources (LEDs) causes that more and more practical problems require the solutions. Also in the glare assessment at workplaces. We hope that our article will facilitate the work of experts dealing with these issues and people who conduct research on the development of measurement methods of the glare.

This paper was based partly on the results of a research task carried out within the scope of the second stage of the National Programme "Improvement of safety and working conditions" partly supported in 2011–2013 — within the scope of research and development — by the Ministry of Science and Higher Education/National Centre for Research and Development. The Central Institute for Labour Protection – National Research Institute (CIOP-PIB) was the Programme's main co-ordinator.

***Authors**: prof. Dariusz Sawicki PhD, DSc, Warsaw University of Technology, Institute of Theory of Electrical Engineering, Measurement and Information Systems, Warsaw, Poland, e-mail: dariusz.sawicki@ee.pw.edu.pl; prof. Agnieszka Wolska PhD, DSc, Central Institute for Labour Protection - National Research Institute (CIOP-PIB), Warsaw, Poland, e-mail: agwol@ciop.pl; Tobias Porsch, TechnoTeam Bildverarbeitung GmbH, 98693 Ilmenau, Germany, e-mail: Tobias.Porsch@technoteam.de.*

LITERATURA

[1] Wolska A., Glare as specific factor in the working environment. *Przegląd Elektrotechniczny*, 89 (2013), n.1a, 142-144
[2] Light and lighting. Lighting of Work Places. Part 1. Indoor Work Places. European Standard. EN 12464-1: 2011. European Committee for Standardization (CEN), Brussels
[3] CIE, Discomfort glare in the interior working environment. CIE Publication No 55 International Commission on Illumination (CIE). Vienna 1983
[4] CIE, Discomfort Glare in Interior Lighting. CIE Publication No 117 (TC 3–13). International Commission on Illumination (CIE). Vienna 1995
[5] Parsons J.H., Glare, its causes and effects. *The Illuminating Engineer*, 1910, 3, 99-103
[6] Holladay, L.L., The fundamentals of glare and visibility. *J.Opt. Soc. Amer.* 1926, n.12, 271-319
[7] Hopkinson R.G., Bradley R.C., A study of glare from very large sources. *Illum Eng*. 55 (1960), n.5, 288-94
[8] Petherbridge P, Hopkinson RG. 1950. Discomfort glare and the lighting of buildings. *IESTrans*. XV (1950), n.2, 39-79
[9] Hopkinson R.G., The multiple criterion technique of subjective appraisal, *Quarterly Journal of Experimental Psychology*, 1950, n.2,3, 124-131
[10] Hopkinson R.G., Evaluation of glare. *Illum Eng*. 52 (1957), n.6, 305-316
[11] Hopkinson R.G., Glare from daylighting in buildings. *Appl Ergon*. 1972, n.3, 206-215
[12] De Boer J.B., Visual perception in road traffic and the field of vision of the motorists. In: Public Lighting (de Boer J,B, ed.) Philips Technical Library, Eindhoven 1967. pp.11-96
[13] De Boer J.B., Quality criteria for the passing beam of motocar headlights. Presented at the GTB Meeting in Walldorf, West Germany, 1973.
[14] Carlucci S., Causone F., De Rosa F., Pagliano L. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. *Renewable and Sustainable Energy Reviews*. 47 (2015), 1016-1033
[15] Sawicki D., Wolska A., *The unified semantic glare scale for GR and UGR indexes,* Proc. of the 2016 IEEE Lighting Conference of the Visegrad Countries (Lumen V4), 13-16.09.2016 Karpacz, Poland
[16] Summers A.J. Lighting and the Office Environment: A Review. *Australian Journal of Physiotherapy*, 35 (1989), Issue 1, 15-24
[17] Clear R.D., Discomfort glare: what do we actually know? *Lighting Research & Technology*, 45 (2013), n.2, 141-158
[18] Pierson C., Wienold J., Bodart M. Review of Factors Influencing Discomfort Glare Perception from Daylight. *LEUKOS The Journal of the Illuminating Engineering Society*. 14 (2018), Issue 3, 111-148
[19] Paul B. The assessment of light sources, 1997, M.Sc Thesis, University of Cape Town, South Africa
[20] Paul B, Einhorn H.D., Discomfort glare from small light sources, *Lighting Research & Technology*, 31 (1999), n.4, 139-144
[21] Osterhaus W.K.E., Bailey L.L., Large area glare sources and their effect on visual discomfort and visual performance at computer workstations. Conference: Industry Applications Society Annual Meeting, 1992., Conference Record of the 1992 IEEE DOI: 10.1109/IAS.1992.244537
[22] Hopkinson R.G., Collins W.M., An Experimental Study of the Glare from a Luminous Ceiling, *Transactions of the Illuminating Engineering Society (London), Lighting Research & Technology* 28 (1963), n.4, 142-148
[23] Fekete J., Sik-Lányi C., Schanda J., Spectral discomfort glare sensitivity investigations, *Ophthalmic & Physiological Optics*, 30 (2010), n.2, 182-187
[24] Flannagan M.J., Subjective and objective aspects of headlamp glare: effects of size and spectral power distribution, 1989, The University of Michigan Transportation Research Institute Ann Arbor, Michigan 48109-2150, U.S.A. Report No. UMTRI-99-36
[25] Guth S.K., Comfortable brightness relationships for critical and casual seeing, *Illuminating Engineering*, 46 (1951), n.2, 65
[26] Lulla A.B., Bennet C.A., Discomfort glare: Range effects, *Journal of IES*, 10 (1981), n.2, 74
[27] Kent M., Fotios S., Altomonte S., An experimental study on the effect of visual tasks on discomfort due to peripheral glare, *LEUKOS*, 2018 , 1-12, DOI: 10.1080/15502724.2018.1489282
[28] Kim W., Kim J.T.A., Position Index Formula for Evaluation of Glare Source in the Visual Field , *Indoor and Built Environment*. 20 (2011), issue 1, 47-53.
[29] Luckiesh M., Guth S.K., Discomfort glare and angular distance of glare source, *Illuminating Engineering*, 41 (1946), n.6, 485

[30] Wonwoo K., Yasuko K., MELO O., Position Index for a Glare Source in the Whole Visual Field. Journal of the Illuminating Engineering Institute of Japan, 88 (2004), n.07
[31] Ostberg O., Stone P.T., Benson R.A., Free magnitude estimation of discomfort glare and working task difficulty. Goteborg Psychological Reports. 15 (1975), 5, 1.
[32] Sivak M., Flannagan M., Discomfort glare is task dependent. Proc CIE 22 nd Session, Melbourne 1991.
[33] Ma S., Yang Y., Ronnier M., Liu L.X., Assessing and modeling discomfort glare for raw white LEDs with different patterns. *Leukos*, 13 (2017), issue 2, 59-70
[34] Yang Y., Ma S.N., luo M.R., Liu X.Y., Discomfort glare caused by non-uniform white led matrices . Proceedings of 28th CIE Session 2015, Manchester, UK , 27 June – 4 July, 2015, 393-399
[35] Yang, M Ronnier Luo, Ma S.N., Liu X.Y., Assessing glare. Part 1: Comparing uniform and non-uniform LED luminaires, *Lighting Research & Technology*, 49 (2017), n.2, 195-210
[36] Yang, M Ronnier Luo, Ma S-N: Assessing glare. Part 2: Modifying Unified Glare rating for uniform and non-uniform LED luminaires LED luminaires, *Lighting Research & Technology*, 49 (2017), n.6, 727–742
[37] Donners MAH, Vissenberg MCJM, Geedrinck LM, van den Broek-Cools JHF, Buddermeijer –Lock A. A psychophysical model of discomfort glare in both outdoor and indoor applications. Proceedings of 28th CIE Session 2015, Manchester, UK , 27 June – 4 July, 2015, 1602-1610
[38] Schier GH, Hanselaer P, Bracke P, Deconinck G, Ryckaert Calculation of the unified glare rating based on luminance maps for uniform and non-uniform light sources. *Building and Environment*, 84 (2015), 60-67.
[39] Schier GH, Hanselaer P, Van de Perre L, Ryckaert WR, Effectof luminance contrast on the perception of discomfort, Proceedings of 28th CIE Session 2015, Manchester, UK, 27 June – 4 July, 2015, 1870-1876.
[40] Nakamura, Y., Takahashi, R., Sasabe, K.: Prediction of Discomfort Glare of a Non-Uniform Light Source by Use of Its Luminance Image. Proceedings of 28th CIE Session. Manchester 2015. pp. 400- 408.
[41] Funke C, Schierz Ch. Extension of the unified glare rating formula for non-uniform led luminaires. Proceedings of 28th CIE Session 2015, Manchester, UK, 27 June – 4 July, 2015, 1471-1480.
[42] Eble-Hankins M.L. Subjective impression of discomfort glare from sources of non-uniform luminance. Architectural Engineering - Dissertations and Student Research. Paper 1., 2008, University of Nebraska –Lincoln
[43] Eble-Hankins M.L., Waters C.E., Subjective impressions of discomfort glare from sources of non-uniform luminance, *Leukos*, 6 (2009), issue 1, 51–77.
[44] Tashiro T., Kawanobe S., Kimura-Minoda T., Discomfort glare for white LED light sources with different spatial arrangements, *Lighting Research and Technology*, 47 (2015), Issue 3, 316-337.
[45] Manabe H., The assessment of discomfort glare in practical lighting installations. Otemon Economic Studies. 1976, 9. Otemon Gakuin University, Osaka, Japan
[46] Stone P.T., Harker S.D.P., Individual and group differences in discomfort glare responses. *Lighting Research and Technology* 5 (1973), issue 1, 41-49
[47] Boyce P.R., Crisp V.H.C., Simons R.H., Rowlands E., Discomfort glare sensation and prediction. Proc CIE 19th Session, Kyoto 1979, 260
[48] Akashi Y., Muramatsu R., Kanaya S., Unified Glare Rating (UGR) and subjective appraisal of discomfort glare. *Lighting Research and Technology*, 28 (1996), Issue 4, 199-206
[49] Boyce P.R., Hunter C.M., Inclan C., Overhead glare and visual discomfort. *Journal of IES*, winter 2003, 73-88
[50] Sawicki D. Wolska A. Discomfort glare prediction by different methods. *Lighting Research & Technology*, 47 (2015), issue 6, 658-671
[51] Geerdinck L.M., Glare perception in terms of acceptance and comfort [graduation report]. Eindhoven University of Technology 2012
[52] Geerdinck L.M., Van Gheluwe J.R., Vissenberg M.C.J.M., Discomfort glare perception of non-uniform light sources in an office setting, *Journal of Environmental Psychology*. 39 (2014), 5-13
[53] Cai H., Chung T., Evaluating discomfort glare from non-uniform electric light sources. *Lighting Research & Technology*, 45 (2013), issue 3, 267-294
[54] Lou D., Deng S., Bian J., Van der Burgt P.J.M., Evaluation of Glare from Non-Uniform Indoor Luminaires. Proceedings of 28th CIE Session. Manchester 2015. 1860-1869
[55] Iacomussi P., Radis M., Rossi G., Rossi L., Visual Comfort with LED Lighting. *Energy Procedia*, 78 (2015), 729-734
[56] Melo O., An Assessment on the Limitations of the Unified Glare Rating (UGR) System. Comparison between Eastern and Western Subjects. Kyushu University - Graduate School of Human-Environment Studies, Universidade de Kyushu, Japão.,25.03.2002, 133-136
[57] Wolska A., Sawicki D. Evaluation of discomfort glare in the 50+ elderly: experimental study International *Journal of Occupational Medicine and Environmental Health*, 27 (2014), n.3, 444-459
[58] Bargary G., Jia Y., Barbur J.L., Mechanisms for discomfort glare in central vision. *Investigative Ophthalmology & Visual Science*, 56 (2015), n.1, 464-471
[59] CIE. Research Roadmap for Healthful Interior Lighting. International Commission on Illumination (CIE), ED/TR TC 3-46, 2016
[60] Akashi Y., Asano S., Kakuta Y. Visual Mechanisms of Discomfort Glare Sensation Caused by LEDs. Proc. of the CIE Centenary Conference Towards a New Century of Light, 15-16 April 2013, Paris, France, 327-330
[61] Cai H., Chung T., Evaluating discomfort glare from non-uniform electric light sources. *Lighting Research & Technology*, 45 (2013), issue 3, 267-294
[62] Sendrup P., Generalization of the unified glare rating method: a proposal and laboratory test. *Lighting Research & Technology*. 33 (2001), issue 4, 243-257
[63] Berman S.M., Bullimore M.A., Bailey I.L., Jacobs R.J. The Influence of Spectral Composition on Discomfort Glare for Large-Size Sources. *Journal of the Illuminating Engineering Society*, 25 (1996), n.1
[64] Bullough J.D., Brons J.A., Qi R., Rea M.S.,. Predicting discomfort glare from outdoor lighting installations. *Lighting Research & Technology*, 40 (2008), 225–242
[65] Sweater-Hickcox K.,Narendran N., Bullough J.D., Freyssinier J.P. Effect of different coloured luminous surrounds on LED discomfort glare perception. *Lighting Research & Technology*. 45 (2013), issue 4, 464-475
[66] Nonne J., Renoux D., Rossi L. Metrology for solid-state lighting quality. Proc. of The 16th International Congress of Metrology. October 7-10th 2013, Paris, France. 14004, 1-8
[67] Jiang C-J., Sun C-C., Chen Y-C. Yang T-H., Chang N., The correlation of veiling luminance and unified glare rating with a transfer function. *Lighting Research & Technology*. 46 (2014), issue 5, 587–592
[68] Rea M.S., Mou X., Bullough J.D. Scene brightness of illuminated interiors. *Lighting Research & Technology*. 48 (2016) issue 7, 823-831
[69] Kim J.T., Shin J.Y., YUN G.Y. Prediction of discomfort glare from windows: Influence of the subjective evaluation of window views. Proc. of The 5th International Symposium on Sustainable Healthy Buildings (SHB2011), Seoul, Korea. 10 February 2011. 283-289
[70] Karlsen L., Heiselberg P., Bryn I., Johra H. Verification of simple illuminance based measures for indication of discomfort glare from windows. *Building and environment*. 92 (2015), 615-626
[71] Kim W., Koga Y., Effect of local background luminance on discomfort glare. *Building and Environment*, 38 (2004), 1435-1442
[72] Kim W., Kim J.T., Effect of Background Luminance on Discomfort Glare in Relation to the Glare Source Size. *Indoor and Built Environment*, 19 (2010), n.1, 175-183
[73] Kim W., Han H., Kim J.T. The position index of a glare source at the borderline between comfort and discomfort (BCD) in the whole visual field. *Building and Environment*, 44 (2009), 1017-1023
[74] Tyukhova Y.I., Discomfort glare from small, high luminance light sources in outdoor nighttime environments (PhD thesis). 2015, University of Nebraska – Lincoln, USA,

[75] Altomonte S., Kent M.G., Tregenza P.R., Wilson R. Visual task difficulty and temporal influences in glare response. *Building and Environment*. 95 (2016), 209-226
[76] Kent M.G., Altomonte S., Tregenza P.R., Wilson R., Discomfort glare and time of day. *Lighting Research & Technology*. 47 (2015), issue 6, 641-657
[77] Tuaycharoen N., Tregenza P.R. Discomfort glare from interesting images. *Lighting Research & Technology*. 37 (2005), n.4, 329-341
[78] Littlefield R. Theory of the "No-Parallax" Point in Panorama Photography. Version 1.0, February 6, 2006. Availavle from http://www.janrik.net/PanoPostings/NoParallaxPoint/TheoryOfTheNoParallaxPoint.pdf (last accessed 09.11.2018)
[79] Entrance Pupil Database. https://wiki.panotools.org/Entrance_Pupil_Database (last accessed 09.11.2018)
[80] Finding The No Parallax Point. http://www.reallyrightstuff.com/finding-the-no-parallax-point (last accessed 09.11.2018)
[81] Reinhard E., Ward G., Pattanaik S., Debevec P., *High Dynamic Range Imaging*. Morgan Kaufmann 2006
[82] LMK Mobile Advanced. Documentation and Instruction Manual of the TechnoTeam's LMK Photometer System. Available also from http://www.technoteam.de/ (last accessed 15.12.2017)
[83] Camera Sensor Ratings by DxO Mark. http://www.dxomark.com/index.php/Cameras/Camera-Sensor-Ratings/%28metrics%29/ (last accessed 23.01.2017)
[84] Canon EOS 550D Instruction Manual. Retrieved 29 October 2013, from http://www.canon-europe.com/support/consumer_products/products/cameras/digital_slr/eos_550d.aspx?type=manuals&language=EN.
[85] Sawicki D., Wolska A., (2013). Algorithm of HDR image preparation for discomfort glare assessment. *Przeglad Elektrotechniczny*, 89 (2013), n.2a, 87-90
[86] Wolf S. Entwicklung und Aufbau eines Leuchtdichte-Analysators zur Messung von Blendungskennzahlen. PhD Thesis. Technische Universität Ilmenau 2004.
[87] Porsch T., Funke C., Schmidt F., Schierz Ch., Measurement of the Unified Glare Rating (UGR) based on using ILMD. Proc. of the 28th CIE SESSION, Manchester, UK, June 28 - July 4, 2015. 536-542