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TECHNICAL REPORT

Discomfort Caused by Glare from Luminaires with a Non-Uniform Source Luminance

CIE 232:2019

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Descriptor: Electrical lighting design
Luminaires
Interior Lighting
Lighting of working environment
Evaluation of lighting installations

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3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
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5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

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Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen berichtet und überprüft werden, sowie neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Joint Technical Committee 7 of Division 1 "Colour and Vision" and Division 3 "Interior Environment and Lighting Design" and has been approved by the Board of Administration and by Divisions 1 and 3 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by all with an interest in excellence in light and lighting. The information provided here is advisory, and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique mixte (JTC) 7 de la Division 1 "Vision et Couleur" et Division 3 "Environnement intérieur et étude de l'éclairage" et a été approuvé par le Bureau et par Divisions 1 et 3 de la Commission Internationale de l'Eclairage. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par tous ceux qui s'intéressent à l'excellence de la lumière et de l'éclairage. Les informations fournies ici sont données à titre indicatif et non obligatoire.

Dieser Technische Bericht ist vom gemeinschaftlichen Technischen Komitee (JTC) 7 der Division 1 "Sehen und Farbe" und Division 3 "Innenraum und Beleuchtungsentwurf" ausgearbeitet und vom Vorstand sowie Division 1 und Division 3 der Commission Internationale de l'Eclairage gebilligt worden. Das Dokument berichtet über den derzeitigen Stand des Wissens und Erfahrung in dem behandelten Gebiet von Licht und Beleuchtung. Es ist zur Verwendung durch alle an Licht- und Beleuchtungsqualität Interessierte bestimmt. Die in diesem Dokument gegebenen Informationen sind eine Empfehlung und keine Vorschrift.

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The following members of JTC 7 “Discomfort caused by glare from luminaires with a non-uniform source luminance” took part in the preparation of this Technical Report. The committee comes under Division 1 “Vision and Colour” and Division 3 “Interior Environment and Lighting Design”

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DISCOMFORT CAUSED BY GLARE FROM LUMINAIRES WITH A NON-UNIFORM SOURCE LUMINANCE

Summary

In 1995 the CIE Technical Committee 3-13 developed the Unified Glare Rating (UGR) to predict discomfort glare for indoor lighting systems. For practical reasons, the UGR is based on the average source luminance. The introduction of LEDs in general lighting enabled many new luminaire designs, sometimes with unprecedented high luminance contrasts. The literature review presented in this report shows that UGR tends to underestimate the discomfort provoked by such luminaires with highly non-uniform source luminance. Several UGR correction methods are evaluated by comparison to experimental data on experienced discomfort from uniform and non-uniform light sources. The preferred method involves a precise definition of the glare source area based on a luminance image of the source. This method solves the discrepancies between UGR and perceived glare from non-uniform light sources. To guide future work on glare prediction methods, the remaining shortcomings of UGR are briefly reviewed.

INCONFORT CAUSE PAR L'EBLOUISSEMENT PROVENANT DE LUMINAIRES A LUMINANCE NON-UNIFORME

Résumé

En 1995 le Comité Technique 3-13 de la CIE a développé une formule de prédiction de l'éblouissement d'inconfort pour l'éclairage intérieur, appelée Unified Glare Rating (UGR). Pour des raisons pratiques, l'UGR se base sur la luminance moyenne de la source éblouissante. Le développement des LEDs en éclairage général a fait émerger une grande variété de nouveaux modèles de luminaires, entraînant parfois des contrastes de luminance élevés au sein du luminaire, jamais vu auparavant. La recherche bibliographique présentée dans ce rapport montre que l'UGR a tendance à sous-estimer l'inconfort provoqué par de tels luminaires présentant une très forte non-uniformité de luminance. Plusieurs méthodes de correction de l'UGR sont évaluées en les comparant à des données expérimentales d'inconfort ressenti face à des sources lumineuses uniformes et non-uniformes. La méthode finalement retenue se base sur une définition précise de la surface de la source éblouissante à partir d'une image de luminance de celle-ci. Cette méthode supprime les divergences entre le niveau d'éblouissement prédit par l'UGR et l'éblouissement réellement perçu. Pour orienter les futurs travaux sur les méthodes de prédiction de l'éblouissement, les limites restantes de l'UGR sont brièvement résumées.

PSYCHOLOGISCHE BLENDUNG VON LEUCHTEN MIT INHOMOGENER LEUCHTDICHTESTRUKTUR

Zusammenfassung

Im Jahre 1995 entwickelte das Technische Komitee 3-13 der CIE das Unified Glare Rating (UGR) zur Vorhersage der psychologischen Blendung in Innenräumen. Aus praktischen Gründen basiert das UGR-Verfahren auf einer mittleren Leuchtdichte der Blendquelle. Die Einführung von LEDs in der Allgemeinbeleuchtung ermöglichte viele neue Leuchtdesigns, die teilweise zu unvorhergesehen hohen Leuchtdichtekontrasten innerhalb der Leuchte führten. Die in diesem Report vorgestellte Literaturrecherche zeigt, dass UGR zu einer Unterschätzung des durch die Blendung hervorgerufenen Unbehagens tendiert, die von solchen Leuchten mit stark inhomogener Leuchtdichtestruktur hervorgerufen wird. Mehrere Methoden zur Korrektur des UGR-Verfahrens werden mittels experimenteller Daten bewertet, indem die Werte aus den Korrekturmethode mit dem wahrgenommenen Unbehagen aufgrund der Blendung von homogenen und inhomogenen Lichtquellen verglichen werden. Die bevorzugte Methode enthält eine präzise Definition der Blendquellenfläche, basierend auf

einem Leuchtdichtebild der Blendquelle. Diese Methode behebt die Diskrepanzen zwischen UGR und der wahrgenommenen Blendung von inhomogenen Lichtquellen. Als Ausblick und Hilfestellung für zukünftige Arbeiten zu Blendungsvorhersagemethoden werden die verbleibenden Schwächen von UGR kurz dargestellt.

1 Introduction and scope

Discomfort glare is an aspect of visual comfort that is relevant for determining the quality of a lighting system. It is the type of glare that occurs when people complain about visual discomfort from bright light sources, even when the brightness is not impairing vision. In contrast with so-called disability glare, which is caused by light scattering in the eye, the mechanism for discomfort glare is not well understood. It is usually measured by using subjective evaluation questionnaires. Several empirical formulae based on subjective glare evaluations have been proposed over the past 60 years to predict the degree of discomfort for various types of light sources, electric lighting or daylighting, and for various applications in indoor or outdoor lighting (see e.g. Boyce, 2013).

For indoor lighting, it is generally agreed that discomfort glare produced by an individual source basically depends on four main parameters: the source luminance in the direction of the observer, L_s , the solid angle subtended by the source at the observer's eye, ω , the angular position of the source in the observer's field of view, indicated by the position index, p , and the general field luminance controlling the adaptation level of the observer's eye, or background luminance, L_b . Moreover, it is also acknowledged, that L_s must be greater than $500 \text{ cd}\cdot\text{m}^{-2}$ to $700 \text{ cd}\cdot\text{m}^{-2}$ for discomfort to exist (CIE, 1983). In 1995 the CIE Technical Committee 3-13 developed a practical discomfort glare evaluation system for indoor lighting, including the four above mentioned parameters, which resulted in the Unified Glare Rating, UGR (CIE, 1995). The formula for calculation of a numerical value of UGR, R_{UG} , is expressed by Equation (1):

$$R_{UG} = 8 \log \left[\frac{0,25}{L_b} \sum \frac{L_s^2 \omega}{p^2} \right] \quad (1)$$

where the summation is over all sources in the field of view and where

- L_s is the source luminance in the direction of the observer;
- ω is the solid angle subtended by the source at the observer's eye;
- p is the position index, which depends on the angular position of the source in the observer's field of view;
- L_b is the general field luminance controlling the adaptation level of the observer's eye, or background luminance.

It should be noted that this UGR formula is valid only for sources which have a subtense at the eye between $0,0003 \text{ sr}$ and $0,1 \text{ sr}$ (which corresponds approximately to the range covered by square luminaires with sides of 5 cm up to 1 m at 3 m distance). For smaller sources, the discomfort glare is related to luminous intensity rather than to luminance (CIE, 2002). It should also be noted that the original work on UGR suggested that only luminous areas with a luminance above $500 \text{ cd}\cdot\text{m}^{-2}$ should be counted as glare source area, but there was no described procedure for doing so at the time (CIE, 1995).

With the introduction of light-emitting diodes (LEDs) in general lighting, interest in the topic 'discomfort glare' arose again. The possibility of using LEDs in general lighting allows for many new luminaire types. However, the high luminance contrasts and high local peak luminance in the exit window of some of these luminaires seemed to provoke more discomfort glare than expected based on calculated UGR values. This discrepancy between the calculated UGR and the subjective discomfort glare by these luminaire types gave rise to an increasing number of published studies on this topic.

Many studies show that for the same average luminance, there is a significant difference in discomfort glare experience between uniform and non-uniform luminaires, and subsequently imply that UGR, using the average luminance for L_s , is not always a reliable measure for discomfort glare perception of those non-uniform luminaires.

In April 2013, it was proposed during the Division 3 meeting in Paris to start a new Technical Committee on this topic. Given the fundamental nature of discomfort glare, it was decided to form a Joint Technical Committee together with Division 1. The following Terms of Reference for JTC 7 were approved by the BA in October 2014:

- 1) To review the literature on glare from non-uniform light sources to identify the parameters that influence the discomfort prediction (UGR) and define limits to the applicability of the UGR formula.
- 2) To propose a correction to the UGR formula that takes into account the non-uniformity of glare sources.

In this report, a literature review on the effect of various uniformity parameters on perceived glare is provided in Clause 2, together with a literature overview of proposed uniformity corrections to the UGR formula. Clause 3 describes the correction to UGR. This correction is selected on the basis of the following criteria:

- 1) good agreement with empirical data on perceived glare from non-uniform sources;
- 2) coverage of the worst-case situation (do not allow a good UGR score to potentially glare sources);
- 3) minimum deviation from the original definition of UGR;
- 4) easy implementation for lighting designers and lighting manufacturers (minimum effort).

Besides non-uniformity of the glare source, there are other issues that may require further improvements or a complete revision of the UGR method in the near future. Clause 4 provides a brief summary of such issues, related to, amongst others, spectral effects and overhead glare.

NOTE Though most studies have been carried out with LED-based light sources, the conclusions may be generalized to any compact bright light source with similar brightness and size. The use of the word “LED” in the following should therefore be interpreted as “a small bright-light source”.

2 Literature on glare caused by non-uniform light sources

The literature on glare caused by non-uniform light sources was reviewed by Geerdinck et al. (2016). This review forms the basis of the overview presented here. In all, 60 papers were reviewed. Although the first papers on discomfort glare from non-uniform light sources date from the seventies, most of the reviewed articles are from a more recent date (2012–2016). Papers originate from many different regions in the world, Asia and America as well as Europe are represented. In 43 of these papers the difference between uniform and non-uniform luminaires was investigated. In these papers various applications are covered, e.g. office lighting, industrial lighting, sports lighting, street lighting and automotive head lighting.

Many studies performed glare perception research in a laboratory set-up, with prototype luminaires and the possibility to vary lighting parameters in a systematic way. But studies with commercially available luminaires are done as well, including studies in simulated office environments. In a laboratory set-up different glare angles can be investigated separately, which is not possible in a more field-study-like set-up, where participants have the freedom to look in more directions. However, generalization is probably more reliable in the latter case, as it is more directly comparable to a realistic situation.

Most studies evaluate discomfort glare using a subjective (semantic) scale, but also studies were found that assessed the effects of non-uniform light sources on objective physiological visual fatigue measures or even on visibility, approaching the field of disability glare. A complicating factor is that discrepancies between various studies may have a methodological cause, related to effects like range bias and anchor bias, or to differences in interpretation of multiple-criterion glare scales (see e.g. (Kent et al., 2019), or (Geerdinck, 2012)). Some studies demonstrate that the UGR is not always a reliable predictor for glare experience, and

investigate which factors and parameters are of influence. Other studies try to capture the applicability boundaries of the UGR. Many papers (19 in total) suggest alternative ways to predict discomfort glare, with improved reliability for both uniform and non-uniform luminaires. These proposals vary between a whole new way to approach glare perception prediction and a small modification of the currently used UGR formula.

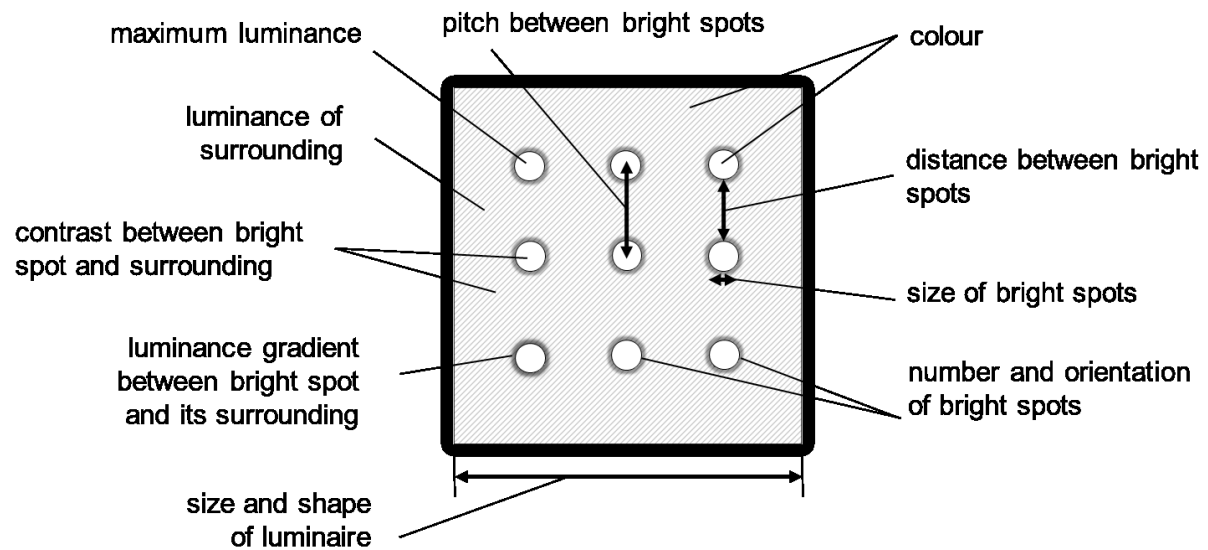
In the next clause, the most relevant parameters affecting discomfort glare of non-uniform sources are discussed, the state-of-the-art measurement of non-uniform sources is addressed, and an overview is given of the offered alternatives to better predict discomfort glare, with a focus on suggestions for limited modifications of the UGR formula.

2.1 Overview of types of non-uniformity

The concept 'non-uniform' is approached in many different ways. Some studies compare a completely uniform light source with a pixelated matrix light source, with bare LEDs that are visible. These studies investigate the effect of variations in pitch (distance) between LEDs, the density of the LEDs, and the size (surface area) of the light source. Other variations of non-uniformity are also studied. Some studies vary the luminance ratio (peripheral/source), or the luminance gradients between LED and its surrounding, or the percentage luminous surface (luminance area ratios). Additionally, some studies investigate the effect of non-uniformity for variations in different external parameters, such as viewing direction (direct/peripheral view), background luminance and task difficulty.

In many studies, the non-uniformity of the luminaire is expressed as the ratio between maximum luminance and the average luminance of the luminaire. But other aspects of this non-uniformity, which indeed can influence the glare perception, are not considered. Variables that have not always been considered in the literature include the size of the LEDs, the number of LEDs per surface area and the luminance gradient between the maximum peak and its direct surrounding in the exit window. The effect of these different parameters of non-uniformity on discomfort glare, as reflected in Figure 1, are discussed separately in later clauses. It is good to mention however, that various interactions between these parameters exist (and not all of them are known). For example, in two overview articles Clear (2012) and Hara (2016) showed that the glare models and the position index need to be reconsidered, as the current glare models have a bad correlation with Luckiesh and Guth data (1949), and the position index depends upon various glare source parameters.

NOTE Throughout this report, LED pitches and other distances can be defined either as distances in real space (measured in metres) or as angular displacements with respect to an observer's eye or a measurement device (measured in degrees). The type of pitch dimension will be clarified in the context, wherever that is relevant. Similarly, source areas may be measured either in square metres or its respective solid angle in steradians.



Observer related parameters:

position in field of view, viewing distance, background luminance, type of task, ...

NOTE The exit window, or light emitting area, of the luminaire can have different sizes and shapes, and different parameters to describe the luminance distribution inside the exit window, as indicated in the figure. The effect on glare of these luminance pattern parameters may depend upon observer parameters, such as viewing distance and background luminance.

Figure 1 – Luminance pattern related parameters that influence glare perception

2.2 Comparison of uniform and non-uniform light sources

In many papers the difference in discomfort glare from uniform and non-uniform glare sources is compared. Although non-uniformity is interpreted differently in the various studies, most authors conclude that non-uniform luminaires are perceived as more glaring than uniform sources, when the average luminance and glare source area are kept constant (e.g. Eberbach, 1974; Waters et al., 1995; Kasahara et al., 2006; Takahashi et al., 2007a; Lee et al., 2007; Jung et al., 2009; Kim and Kim, 2010b; Tashiro et al., 2011; Bullough, 2011; Bullough and Hickcox, 2012; Erdem et al., 2012; Hara and Hasegawa, 2012; Ayama et al., 2013; Funke and Schierz, 2014; Geerdinck, 2014a; Geerdinck et al., 2014b; Schmits and Moskvina, 2014; Donners et al., 2015; Funke and Schierz, 2015; Ixaina et al., 2015; Scheir et al., 2015b; 2016a; 2016b; Yang et al., 2015; 2016; 2017; 2018a, 2018b; 2018c, Iwata et al., 2016; Mochizuki et al., 2011).

One study shows a different result: in the work of Eble-Hankins (2008), the uniform glare source is slightly more glaring than non-uniform glare sources. One reason for this may be that lined luminance patterns were used, which could have different effects on discomfort glare perception (Wilkins et al., 1984; Wilkins, 2015).

2.3 Effect of luminance contrast

Most of the earlier mentioned studies investigated the effect of the non-uniformity in a quantitative way, and expressed it as a luminance ratio, using for example $L_{\min} / L_{\max}$ or a Weber contrast ($\Delta L / L_{\text{avg}}$) or a Michelson contrast ($(L_{\max} - L_{\min}) / (L_{\max} + L_{\min})$) or a luminance uniformity $L_{\text{avg}} / L_{\max}$, where $L_{\min}$ is the minimum luminance, L_{avg} is the average luminance, $L_{\max}$ is the maximum luminance, and ΔL is the difference between the source luminance and the background luminance. Conclusively, it was observed that the smaller the uniformity (i.e. the greater the difference in luminance) the higher the perceived discomfort glare (e.g. Hara and Hasegawa, 2012). The uniformity decreases in the following cases:

- smaller area ratio between LEDs and the rest of the glare source (that includes smaller LED size, less LEDs per area and steeper luminance gradients);
- higher luminance of LEDs inside the luminaire;
- higher luminance ratio between LEDs and immediate surrounding.

In many studies however, the presented stimuli have been a combined variation of these parameters. For example, in case of a constant average luminance, a smoother luminance gradient around the LEDs will result in a lower peak luminance at the same time (e.g. Tashiro et al., 2011; 2015; Higashi et al., 2013; Geerdinck et al., 2014).

2.4 Effect of LED size and LED number

In several studies the LED size and LED number inside the glare source were varied at the same time while keeping the average luminance of the glare source constant (e.g. Kasahara et al., 2006; Lee, 2007; Takahashi et al., 2007a; 2007b, Hara and Hasegawa, 2012, Yang et al., 2015; 2016; 2017; 2018a; 2018b; 2018c). All scientists found increased glare for decreasing LED sizes and LED number. This makes sense, because smaller LEDs or a fewer number of LEDs per surface area whilst preserving a constant average luminance, require a higher luminance per LED.

2.5 Effect of LED distance

A few scientists systematically investigated the effect of LED distance (or LED pitch) on discomfort glare. The first study was presented by Eberbach (1974), who used halogen lamps as parts of the glare source. For the parameters he used ($L_{\max}$ up to 5 000 $\text{cd}\cdot\text{m}^{-2}$, $L_{\max} / L_{\min}$ up to 2 000, pitch between 0° and 3°), he could not find an effect of peak luminance or spot pitch. Many years later, these results could be confirmed for LED matrix sources by Funke and Schierz (2014; 2015) and Tashiro et al. (2015), who used higher peak luminances (up to $4 \times 10^5 \text{ cd}\cdot\text{m}^{-2}$), different glare angles (0° up to 30°) and similar luminance ratios (up to 1 000) and LED pitches ($0,2^\circ$ to 5°). Eble-Hankins (2008) used line patterns produced by a projector and found a small effect of the high luminance pitch. She observed the highest discomfort glare perception for line frequencies of 4 cycles per degree. This observation regarding line patterns was also made by Wilkins et al. (1984). Moreover, Donners et al. (2015) reported rising discomfort glare rating for rising LED pitches ($0,037^\circ$ to $0,14^\circ$) at direct view. It was obvious from their data that their biggest LED pitch equals 7 cycles per degree and is close to 4 cycles per degree, which are highlighted by Wilkins et al. and Eble-Hankins. Thus, for direct view into the glare source, it can be concluded, that in the region near the fovea discomfort glare seems to increase with rising LED pitch until an LED pitch of around $0,14^\circ$ is reached. For greater LED pitches, the LED distance has no effect on discomfort glare. At peripheral view, the discomfort glare perception is influenced by glare angle and LED pitch, among other parameters. If the LED pitch is larger than the visual acuity at the corresponding position in the retina, discomfort is generally higher compared to situations where LED pitches are too small to be visually resolved (e.g. Niedling et al., 2014).

2.6 Effect of viewing angle

In several studies the effect of the viewing angle on glare perception was investigated. In these studies, the glare source is usually positioned at or above the viewing direction. In general, the biggest difference between uniform and non-uniform luminaires was observed at foveal view (e.g. Waters et al., 1995). The more peripheral the glare source, the smaller the difference between uniform and non-uniform glare sources (e.g. Takahashi et al. 2007a; 2007b, Eble-Hankins, 2008; Funke and Schierz, 2014; 2015). Mostly at glare angles of 30° or above, the difference in discomfort glare perception due to non-uniformity is nearly imperceptible (Takahashi et al. 2007a; 2007b; Funke and Schierz, 2014; 2015). The specific elevation angle at which no difference in glare perception between uniform and non-uniform exists is not clear and seems to depend upon the application (the effect of lateral displacement from the viewing direction is unknown). For example, Niedling et al. investigated the separation of single LEDs inside a matrix luminaire (Niedling et al. 2014). They found that for streetlight conditions, the subjects cannot resolve LED spots at glare angles greater than